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Noise Radiation Asymmetries in the Delta IV Heavy Rocket

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The role of nozzle configuration on rocket noise radiation is not well understood, particularly for multi-core vehicles where plume interactions may introduce azimuthal asymmetry. While tightly clustered engines are often assumed to radiate axisymmetrically, configurations with spaced nozzles may exhibit directionally dependent acoustic fields. This paper presents results from a measurement campaign conducted during the final Delta IV Heavy launch (NROL-70), supplemented by data from a previous launch (NROL-82), to investigate azimuthal variation in radiated noise. Measurements spanning a wide range of azimuthal angles show a consistent increase in sound pressure and sound power levels along the jet midplane relative to the jet plane. In sound pressure levels, differences of 5 dB are observed near the dominant spectral frequency (~30 Hz). In sound power, differences of ~2.5 dB are observed, particularly around the peak frequency, with smaller but persistent differences at higher frequencies. Strouhal number analysis indicates that the effective source length scale lies between the limits of fully independent and fully merged plumes, suggesting a partially merged interaction regime. These results provide field-scale evidence that multi-core rocket plumes do not behave as independent or fully merged sources but instead form partially coupled turbulent structures that produce directionally dependent acoustic radiation. The findings demonstrate that azimuthal asymmetry in large rocket noise is both angle and frequency dependent and should be considered in modeling of launch acoustics.

Nomenclature

D_e = nozzle exit diameter, m
D_{eff} = effective diameter, m
d = distance from launch pad to measurement location, m
f = frequency, Hz
f_{pk} = spectral peak frequency, Hz
M_e = exit Mach number
n = number of engines
L_p = frequency-dependent sound pressure level, dB re 20 μPa
$L_{p,\mathrm{OA}}$ = overall sound pressure level, dB re 20 μPa
L_w = frequency-dependent sound power level, dB re 1 pW
$L_{w,\mathrm{OA}}$ = overall sound power level, dB re 1 pW
s = the center-to-center spacing between two nozzles, m
Sr = Strouhal number
U_e = plume exit velocity, m/s
W_f = frequency-dependent sound power, W
W_{OA} = overall sound power, W

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I. Introduction

Asymmetric noise radiation and plume shielding from heated, supersonic twin jets is an ongoing area of research in both laboratory environments and aircraft noise studies[1–3]. However, it is not well understood if findings from these smaller-scale or lower velocity and temperature configurations can be directly applied to heavy-lift rockets, nor how interactions evolve as the number of jets increases. The Delta IV Heavy, a now-legacy rocket with three separated cores, provides a unique opportunity to investigate how plume interactions scale with both size and number of nozzles.

A useful conceptual framework for understanding azimuthal asymmetry in multi-core rocket noise can be drawn from classical multiple-scatterer acoustics. In a simplified sense, multiple plumes may behave as independent radiating sources, partially shield one another, or interact to form a coupled radiating structure. The limiting behavior, being independent, fully merged, and partially merged, lead to different directivity patterns and spectral characteristics. The Delta IV Heavy provides a fluid-dynamic analog to this problem, where each "scatterer" is replaced by a high Mach number jet plume. A more detailed discussion of these interaction regimes is provided in Section III.

Previous studies suggest that sound power from multiple jets depends on nozzle spacing, plume temperature, jet velocity, and azimuthal angle. Lubert et al. (2022) noted the potential for significant azimuthal asymmetry as an aspect of clustered rocket nozzles[4]. Kantola (1981) reported on significant variations of up to 4-5 dB between orthogonal azimuthal planes in heated twin jets, with larger nozzle spacings increasing shielding effects[1]. Pineau and Bogey (2021) used large-eddy simulations to investigate acoustic shielding in superheated, supersonic twin jets of various center-to-center spacings and found reductions of up to 2 dB in the jet plane due to plume shielding, while also observing frequency-dependent amplification in the jet midplane and at low polar angles associated with interaction noise and enhanced turbulent structures[2]. These results demonstrate that plume interactions can simultaneously suppress and enhance different components of the acoustic field.

Additional studies have emphasized the importance of plume interaction regimes. Depending on the ratio of nozzle spacing to jet diameter, jets may behave as independent sources, partially merged plumes, or a single jet formed by the immediate merging of plumes after exiting the nozzle. This transition influences both spectral content and directivity, with large-scale turbulent structures, responsible for lower frequency radiation, being sensitive to plume coupling[3]. For rockets, Kellison and Gee reported possible evidence of slight sound power azimuthal asymmetry in NASA's Space Launch System noise at high frequencies, though results were inconclusive[5]. For the Atlas V, Mathews et al. observed that peak frequencies varied with viewing angle, suggesting a transition between single-plume and multi-plume behavior depending on azimuth[6].

Together, these studies indicate that plume-plume interactions play a role in shaping the radiated sound field, but the structure of azimuthal asymmetry in full-scale, multi-core rocket launches remains poorly quantified. In particular, it is unclear whether the sound field is dominated by independent plumes, a fully merged equivalent plume, or an intermediate state. The Delta IV Heavy, with its three spaced cores, provides an opportunity to directly investigate these phenomena and assess how multi-jet interactions manifest in far-field acoustic measurements.

This paper is organized as follows. In Section II, the Delta IV Heavy vehicle is described. Section III contains a discussion on theory and previous studies related to the topic of multi-jet interactions. Section IV contains a summary of the measurements conducted during NROL-82 and NROL-70. In Section V, key results and evidence for asymmetric noise radiation are presented and discussed. Section VI contains conclusions.

II. The Delta IV Heavy Vehicle

ULA's Delta IV Heavy rocket, shown in Figure 1, first took flight on December 21, 2004, and successfully completed 15 launches carrying various payloads for NASA and other government bodies. The Delta IV Heavy was retired after its final mission, NROL-70, on April 9, 2024, from Cape Canaveral Space Force Station. The three RS-68A engines, with exit diameters of $D_e = 2.44$ m (8.0 ft), each produced 3.14 MN of thrust during liftoff, for a total first-stage thrust of 9.42 MN. Though classified as a heavy-lift vehicle, this liftoff thrust is relatively modest compared to Starship Super Heavy (74 MN)[7] [8], Space Launch System (39.1 MN)[5] [9], New Glenn (17.1 MN), and Vulcan Centaur (13.1 MN)[10]. The Delta IV Heavy's sea-level specific impulse was 360 s, resulting in an nozzle exit velocity during liftoff of $U_e = 3.5$ km/s.

The three-engine configuration, each laterally separated by a nozzle center-to-center distance of $s = 5.6$ m ($s/D_e = 2.3$), provides an opportunity to measure asymmetries in the noise radiation. A similar s/D_e of 2.4 was examined by Pineau and Bogey, as well as larger and smaller s/D_e values[2]; of the s/D_e values tested by Pineau and Bogey, the largest reduction in total acoustic energy occurred for s/D_e = 2.3. The viewing geometry associated with this configuration is illustrated in Figure 2. Along the jet plane (90°), an observer sees a single core, while along the jet midplane (0°), all three cores are visible. This geometric difference forms the basis for evaluating directional variation in the radiated sound field.

To facilitate comparison across measurement locations, symmetry across azimuthal quadrants is assumed. That is, variation in radiation from 0° to 90° is taken to be representative of variation over the full 360° field. This assumption is supported by the geometric symmetry of the vehicle, which consists of three identical cores spaced apart, and by the expectation of similar engine operating conditions during liftoff. While local environmental factors may introduce deviations from perfect symmetry, collapsing the data into a single quadrant enables clearer identification of trends associated with plume interaction and shielding.

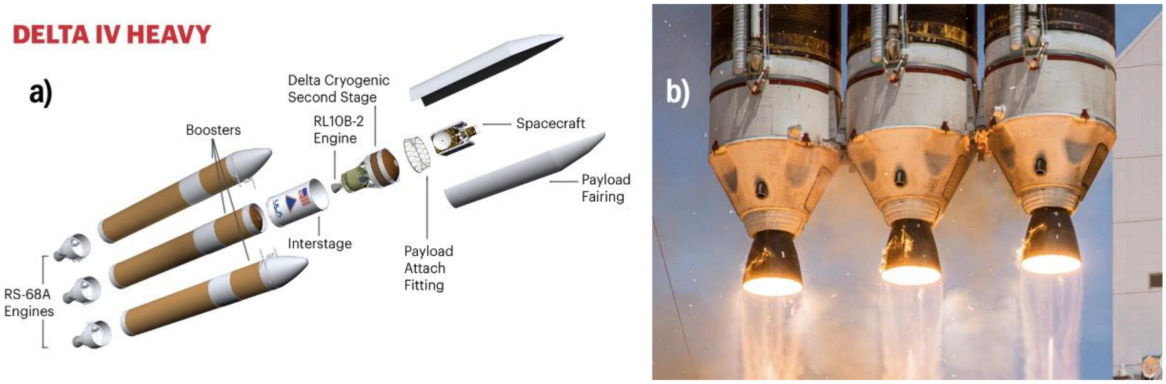

Figure 1. a) Delta IV Heavy rocket diagram. b) Three RS-68A engines during liftoff. Credits: United Launch Alliance.

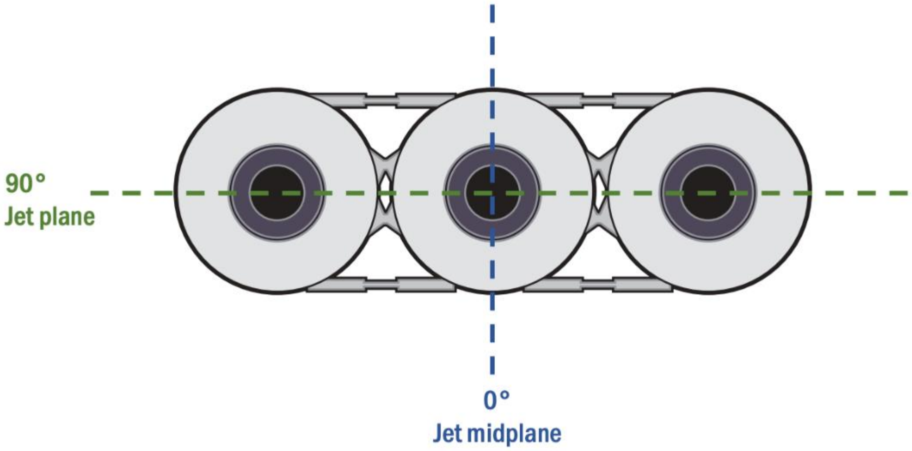

Figure 2. Underside view of the Delta IV Heavy, intersecting planes representing the 'Jet midplane' and 'Jet plane' (centerplane) are shown.

III. Theory of Multi-jet Interaction and Radiation

The acoustic radiation from multi-core rocket configurations can be interpreted through a combination of classical acoustic scattering theory and jet interaction physics. In a simplified representation, each plume may be treated as an individual radiating source arranged with a characteristic spacing relative to its diameter. A schematic representation of this configuration, using three parallel cylinders to represent the plumes, is shown in Figure 3. In the limit of fully independent plumes, each jet radiates as an uncorrelated source relative to the other jets, and the total acoustic field is a superposition of contributions. In this case, directivity is governed primarily by geometric effects such as source spacing and line-of-sight shielding. This behavior is analogous to multiple scatterers in classical acoustics, where obstruction and diffraction produce direction-dependent radiation patterns [10–12]. Under this assumption, each jet can be modeled as an individual source radiating Mach waves, yet the plumes interact with each other and mix at some distance downstream the nozzle exit. For the Delta IV Heavy configuration, this provides an upper bound on azimuthal variation of approximately 4.8 dB between viewing directions where all three plumes are visible and those where only one plume is observed.

At the opposite extreme, plumes may behave as a fully merged jet, forming a single effective source with a characteristic length scale larger than that of an individual nozzle. In this regime, the flow field rapidly combines downstream of the nozzles, and the radiated sound is governed by the collective turbulent structure of the merged plume. This results in a modified spectral content, typically characterized by a shift in dominant frequency due to the increased effective diameter.

Between these limits lies a partially merged regime, in which plumes interact but do not fully coalesce into a single structure. In this case, large-scale turbulent structures may span multiple plumes, while smaller-scale structures remain localized. This intermediate behavior produces complex acoustic radiation, as both shielding and constructive interaction can occur depending on observer location. The degree of coupling in this regime is influenced by s/D, as well as plume temperature and velocity.

Previous experimental and numerical studies have demonstrated the importance of this interaction regime. Kantola observed significant azimuthal variation in heated twin jets, with differences of up to 4–5 dB depending on viewing angle[1]. Pineau and Bogey further showed that plume interaction can simultaneously reduce and enhance sound levels depending on frequency and direction[2]. In their simulations, overall acoustic power was reduced relative to non-interacting jets due to weakening of some turbulent sources, while specific components, particularly broadband shock-associated noise and radiation in the jet midplane, were amplified due to interaction-induced turbulence and additional noise generation mechanisms. These findings indicate that multi-jet systems cannot be described solely by independent or fully merged assumptions.

From an acoustical standpoint, the degree of interaction can also be interpreted in terms of source coherence. Fully independent plumes correspond to low coherence between sources, while a fully merged plume represents a highly coherent structure[3,11]. The partially merged regime corresponds to intermediate coherence, where phase relationships between sources vary spatially and temporally. This has direct implications for both spectral scaling and directivity.

For large rocket plumes, the dominant acoustic radiation is associated with large-scale turbulent structures, which are more sensitive to plume interaction than smaller-scale turbulence[3,11]. As a result, low-frequency radiation is expected to exhibit stronger azimuthal variation than high-frequency components, consistent with observations from multi-jet interaction studies[2]. This provides a physical basis for interpreting both spectral and sound power measurements in terms of plume interaction regimes.

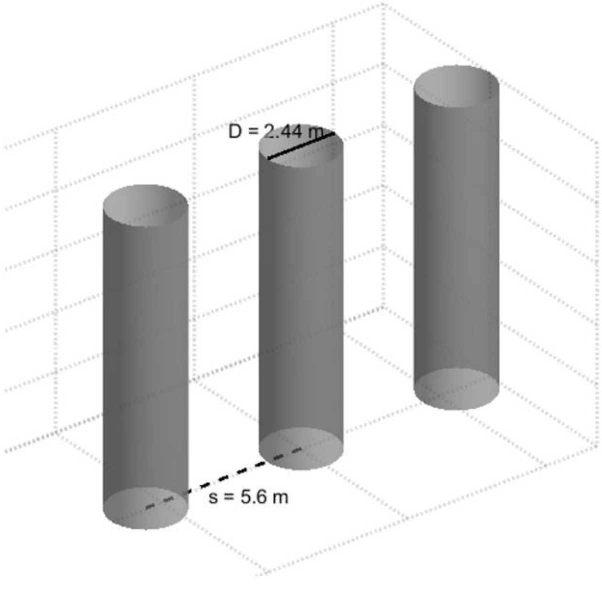

Figure 3. Three cylinders of arbitrary height used to represent the three plumes of Delta IV Heavy. Cylinder diameter and center-to-center spacing are shown.

IV. Measurement Set-up

This paper presents data collected during two launches of the Delta IV Heavy, NROL-82 on April 26th, 2021, and NROL-70 on April 9th, 2024, which was the last ever flight of this rocket. NROL-70 was specifically designed to investigate asymmetries of noise radiation between the jet plane and jet midplane. NROL-82 was used to retroactively support this study. At NROL-82, nine microphones were deployed at five unique locations, shown in Figure 4. During NROL-70, two measurement set-ups were used to detect asymmetric noise radiation. The first, shown in Figure 5, was labeled Site 16. Site 16 consisted of eight microphones located ~520 m from the rocket, spanning an angular aperture of 12.8° azimuthally. Each microphone was a ¼" GRAS 46BG pressure microphone. Data were recorded using the NI 9174 chassis and three 24-bit NI 9232 cards sampling at 102.4 kHz. Microphones were deployed inverted over a hard plastic ground plate, covered by an acoustically transparent windscreen [12]. A GPS clock was used for synchronization with other data acquisition systems used.

In conjunction with Site 16, a broader measurement setup was deployed during NROL-70, this setup is shown in Figure 6. Fourteen measurement sites were positioned 0.15 - 5 km around the launch pad, spanning an angular aperture of 143° relative to the rocket. Some sites had multiple microphones which were also included in the calculations. Microphone deployment for both launches matched that of Site 16, an inverted microphone over a plastic ground plate, data recorded using a 24-bit NI DAQ system. However, in most cases, an NI 9250 module was used in place of the NI 9232, which has a greater fixed voltage range and therefore higher noise floor. Measurement locations beyond five km were excluded from this study as propagation losses and distortions are expected to become greater than that of azimuthal asymmetry noise radiation effects[13]. Also, as previously mentioned, data are presented collapsed into a single, 0 to 90° quadrant to more easily see trends because this study assumes quadrant-to-quadrant symmetry.

Figure 4. Overview of measurement sites during NROL-82 launch. (Google Earth Pro, Image © 2026 Google).

Figure 5. Overview of measurement set-up at site 16. Microphones span an aperture of 12.8°. General rocket location and orientation is noted (not to scale). (Google Earth Pro, Image © 2026 Google).

Figure 6. Overview of measurement sites during NROL-70. Stations ranged from 150 m to 5 km from the launch pad. The 0°, 90°, and 140° lines relative to the rocket are noted. (Google Earth Pro, Image © 2026 Google).

V. Results

A. Data Verification and Sound Pressure Level Analysis

An initial verification of collected data is performed by visually inspecting the pressure-time waveform from each microphone. An example waveform recorded during NROL-70 at a distance of approximately 3.4 km from the launch pad is shown in Figure 7a. The waveform exhibits the expected gradual rise in amplitude as the vehicle ascends, with no evidence of clipping or other instrumentation artifacts.

To assess potential azimuthal asymmetry in the radiated noise field, the overall sound pressure level, $L_{p,\mathrm{OA}}$ and frequency-dependent sound pressure level, $L_p(f)$, are compared for three microphones located at different azimuthal angles relative to the rocket: 0.9° (near the jet midplane), 39.9°, and 87.6° (near the jet plane), as shown in Figure 7b and Figure 7c. The $L_{p,\mathrm{OA}}$ is calculated using a 1-second sliding window, while L_p is calculated over a 3 dB-down region surrounding the maximum $L_{p,\mathrm{OA}}$. Both metrics have been distance-scaled to a common reference distance of 3.01 km, which is the distance from the launch pad to the closest of the three microphones used in the comparison.

The results show a clear increase in measured levels near the jet midplane. The microphone at 0.9° records a maximum $L_{p,\mathrm{OA}}$ approximately 5 dB higher than the microphones at 39.9° and 87.6°. Spectral comparison reveals that this increase is concentrated primarily between 7 Hz and 200 Hz, with a peak difference near 30 Hz. At earlier times in the launch, however, the microphone near 39.9° records higher levels than the other locations, as shown in Figure 7c. This behavior is consistent with the evolution of the acoustic source region during liftoff. Early in the launch, the dominant noise generation occurs closer to the nozzle and launch pad, where the effective radiation angle favors off-axis observers. As the vehicle ascends and the dominant source region moves downstream, the radiation pattern evolves, and increased plume interaction along the jet midplane leads to higher levels at smaller azimuthal angles.

This behavior is consistent with expectations from multi-jet interaction studies, where the large-scale turbulent structures responsible for low-frequency radiation are more strongly influenced by plume interactions and shielding effects[3,11]. In contrast, high-frequency components associated with smaller-scale turbulence tend to be more isotropic, as these structures are less spatially coherent and radiate with largely uncorrelated phase. As a result, the contributions from multiple plumes combine in a more uniform manner across viewing angles, reducing directional variation compared to low-frequency radiation.

The observed increase in low-frequency energy along the jet midplane suggests that plume interactions enhance the radiation of large-scale turbulent structures in these directions. This behavior is consistent with partial plume merging, in which coherent structures span multiple plumes without fully collapsing into a single jet. Similar effects have been observed in multi-jet studies, where interaction between plumes modifies low-frequency radiation through a combination of shielding and constructive interference[1–3].

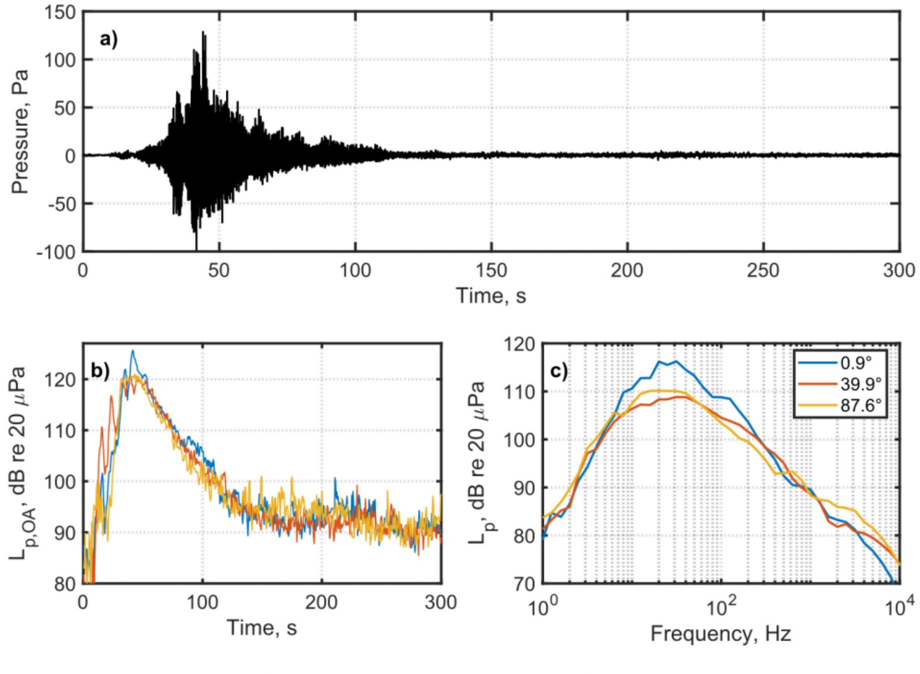

Figure 7. a) The running pressure-time waveform recorded during NROL-70 from ~3 km away. b) The running OASPL for three stations measured during NROL-70 at three different angles relative to the rocket, distance scaled to the nearest station (3.09 km). c) OTO spectra calculated over the 3 dB down period surrounding the maximum $L_{p,\mathrm{OA}}$ for the same three stations and angles measured during NROL-70, scaled to the same distance as b).

B. Strouhal Number Analysis

The next step in understanding the observed azimuthal asymmetry is to examine normalized sound power on a nondimensionalized frequency axis using Strouhal number scaling. The Strouhal number provides a nondimensional relationship between frequency, a characteristic length scale, and flow velocity, allowing spectral features from jets of different sizes and operating conditions to be compared on a common basis. In jet noise studies, it is commonly used to collapse spectral peak frequencies by relating them to the characteristic turbulent structures responsible for acoustic radiation. In this study, sound power level normalization is shown in Eq. (1). Sound power level is then plotted on a Strouhal number axis, defined in Eq. (2).

$$L_{w,\mathrm{norm}} = \frac{W_f}{W_{\mathrm{OA}}} \times \frac{U_e}{D_{\mathrm{eff}}} \tag{1}$$

$$\mathrm{Sr} = f \times \frac{D_{\mathrm{eff}}}{U_e} \tag{2}$$

This study will investigate varying definitions of D_{eff}, which is an effective nozzle diameter or the characteristic length used to nondimensionalize frequency. In NASA SP-8072[14], spectral data from a range of supersonic jets were collapsed using Strouhal scaling based on nozzle diameter and jet velocity, yielding a representative peak Strouhal number of approximately 0.02 for smaller-scale jets typical of laboratory and aircraft conditions. For large rocket plumes, lower Strouhal numbers are generally observed. Recent studies of large-scale rocket noise suggest that a lower value of 0.01 for peak Sr is more appropriate for rockets. For example, the SATURN model developed by Mathews (2026) predicts a peak Strouhal number of 0.01 for modern launch vehicles[15]. SATURN was derived based on data from the Atlas V rocket and validated with Firefly Alpha and Starship Superheavy, and, recently, the Falcon 9 rocket[13].

To evaluate the effective length scale governing noise generation in the Delta IV Heavy, three definitions of effective nozzle diameter, D_{eff}, are considered based on limiting physical cases. First, the exit diameter of a single nozzle, $D_e = 2.44$ m is used, corresponding to a fully independent plume where each jet radiates independently. This case represents a shielding scenario, where the observed field is dominated by single diameter and plume behavior. Second, a fully merged plume is considered, with an effective diameter defined $D_{\mathrm{eff}} = D_e \times \sqrt{n}$, where n is the number of engines. This represents the opposite limit, in which the three plumes behave as a single equivalent jet of equal area as the individual nozzles. Because the expected peak Strouhal number is 0.01, an effective diameter that forces this result is chosen as $D_{\mathrm{eff}} = D_e \times 1.25$, representing partial plume merging as it is larger than a single nozzle diameter yet smaller than the fully merged plume effective diameter.

The resulting Strouhal-scaled spectra for these three cases are shown in . Using a single nozzle diameter results in a peak Strouhal number of approximately 0.008, which is lower than expected for large-scale rocket jets, indicating that this assumption overestimates the degree of plume independence. In contrast, the fully merged diameter yields a peak Strouhal number of approximately 0.014, which is higher than expected, suggesting that this assumption overestimates plume coupling. Agreement with the expected value of 0.01 is achieved only when using the intermediate effective diameter, indicating that the plumes are partially merged rather than the limiting cases.

Previous studies have shown that the primary acoustic source region for large rocket plumes typically occurs at a distance of approximately 15–20 characteristic diameters downstream of the nozzle. Using the measured source location of 55 m downstream reported by Hart et al.[16] the implied nondimensional distance depends on the choice of effective diameter. A figure from Hart et al., reproduced here as Figure 9, illustrates the apparent downstream location of the dominant noise source during early flight of a Delta IV Heavy launch. In this figure, the individual plume cores are clearly separated near the nozzle exits, while signs of instability and interaction begin to develop farther downstream, roughly midway between the nozzles and the dominant noise source region.

When this source location is nondimensionalized using different assumptions for the effective diameter, the single-plume case yields a value that is too large ($22.5 \times D_{eff}$), while the fully merged assumption yields a value that is too small ($13.1 \times D_{eff}$). In contrast, the intermediate effective diameter produces a value of approximately $18 \times D_{eff}$, which falls within the expected range based on previous studies. This result provides additional evidence that the plumes are neither fully independent nor fully merged but instead exist in a partially merged regime. This partial merging offers a physical explanation for the observed azimuthal asymmetry, as the degree of plume interaction varies with viewing angle relative to the rocket.

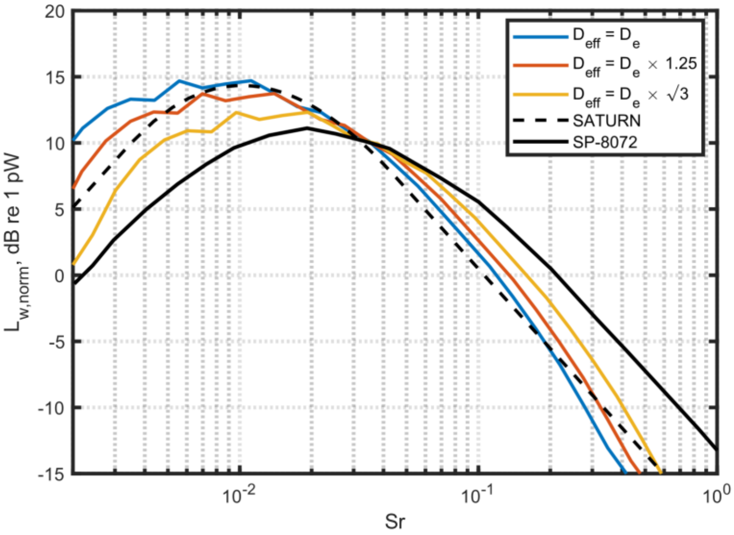

Figure 8. $L_{w,\mathrm{norm}}$ **calculated for three different values of** D_{eff} **and shown on a** Sr **axis, compared to a modern prediction tool, SATURN, and a curve fit to historical jet data published in NASA's SP-8072.**

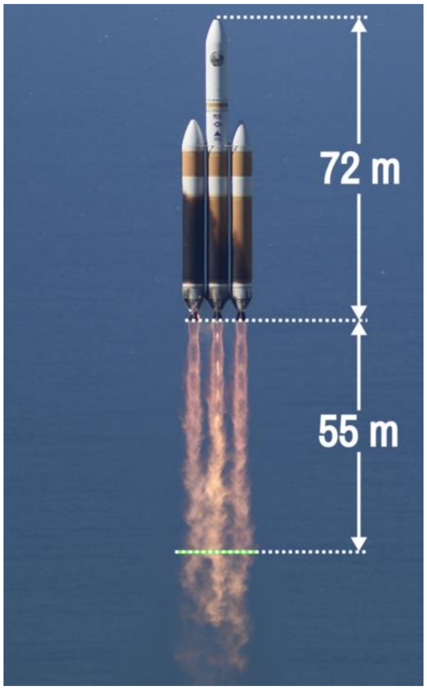

Figure 9. Picture of a Delta IV Heavy rocket shortly after liftoff. The rocket's height is 72 m, and the apparent peak sound source was measured to be 55 m below the nozzles, as shown. Note that the plumes are not yet fully merged at this point. Photo credit: Michael Peterson/USAF

C. Sound Power Analysis

Unlike sound pressure, which is a field property dependent on measurement location, sound power represents a source property of the radiation. By accounting for measurement distance and integrating over the duration of the acoustic event, sound power enables analysis of the radiated acoustic field as a whole and is therefore well suited for examining variation with azimuthal angle. In this study, sound power is initially calculated at each microphone assuming free-field propagation, following methods used in recent work by Kellison and Gee[5] and Hart et al.[17]. This approach implicitly assumes that the radiated field is axisymmetric, such that measurements at a single azimuthal location are representative of the total acoustic output. However, the present dataset includes measurements spanning a wide range of azimuthal angles, enabling a more complete characterization of the radiated field. By incorporating this angular coverage, sound power can be evaluated as a function of azimuth and used to assess deviations from asymmetry, rather than relying solely on the traditional single-microphone assumption. Also, this paper uses two updates to the sound power calculation not included in methods used by Kellison and Gee and Hart et al. First, following Anderson et al.[18], a 1 dB correction is added to account for acoustic radiation into the forward hemisphere, which is not directly measured by ground-based microphones. Second, a 6 dB subtraction is applied to account for ground reflections over hard surfaces, rather than the traditional 3 dB correction, based on recent findings that the historical approach underestimates reflection effects[19].

The sound power levels calculated for the eight microphones at Site 16 is shown in Figure 10. Across a relatively narrow angular aperture of 12.8°, the measured sound power varies by 1.7 dB, with a maximum of 192.4 dB at 89.1° and a minimum of 190.7 dB at 76.3°. A local minimum appears near 81°, followed by a slight increase and subsequent decrease toward smaller angles. These fluctuations may influenced by local environmental factors, such as terrain or nearby structures. However, given the vehicle is ~200 m in altitude when the noise at the peak directivity angle (approximately 70.4°)[17] is emitted, launch pad structures are not expected to fully explain the observed variation. The fact that the microphones were located along a berm could have also skewed the relative null in sound power estimate away from 90°.

To better capture azimuthal trends, sound power is calculated for all available measurements from both NROL-70 and NROL-82 and collapsed into a single 0°-90° quadrant, as shown in Figure 11. This assumption of quadrant symmetry is consistent with the vehicle geometry and allows for clearer identification of trends with angle. The data are grouped into three angular regions: 90°-50°, 50°-30°, and 30°-0°, shown as dashed lines in Figure 11.

In the 90°-50° region, 17 measurements yield a maximum of 193.7 dB at 88.0°, a minimum of 190.6 dB at 81.6°, and a decibel-averaged value of 191.7 dB. In the 50°-30° range, nine measurements produced a maximum of 192.4 dB at 43.2°, a minimum of 190.3 dB at 39.9°, and an average of 191.6 dB. The nine measurements in the 30°-0° range show a maximum of 195.1 dB at 12.0°, a minimum of 192.6 dB at 0.9° and an average of 193.8 dB. This range shows a slight increase in average sound power relative to the other two regions, consistent with the behavior observed in the sound pressure level analysis. This information is summarized in Table 1.

To further examine spectral differences, decibel-averaged sound power spectra for each angular group are shown in Figure 12. The most significant increase in sound power along the jet midplane (30°–0°) occurs near the peak frequency, approximately 30 Hz, where levels are about 2.5 dB higher than in the other angular regions. At lower frequencies, the spectra remain closely grouped, indicating relatively uniform radiation. Above 30 Hz, the 30°–0° spectra consistently remain 1–2 dB above the other regions. This magnitude of variation is consistent with previous multi-jet studies, which have shown that plume interaction and shielding effects produce modest, frequency-dependent differences in radiation above the peak frequency, typically on the order of 1–2 dB[1,2].

These results indicate that azimuthal asymmetry in the Delta IV Heavy noise field is angle-dependent and slightly frequency-dependent. The enhancement of sound power near the peak frequency along the jet midplane is consistent with the findings from the sound pressure level spectra. However, the sound power spectra show that this enhancement persists over a broader frequency range above the peak. This difference is likely due to the increased spatial sampling and angular averaging inherent in the sound power calculation, which captures more gradual, frequency-dependent variations in plume interaction that are not as apparent in comparisons between a small number of individual microphones.

Overall, the observed variation in sound power across azimuth is approximately 2–2.5 dB, with highest levels occurring near the jet midplane. This is consistent with partial plume shielding and interaction effects and remains below the theoretical upper bound of 4.8 dB for three completely uncorrelated monopole sources. These findings reinforce the conclusion that the Delta IV Heavy plume operates in a partially merged regime, producing a directionally dependent acoustic field.

Table 1. Maximum, minimum, and average $L_{p,\mathrm{OA}}$ for the three angular groupings

Angular grouping	Max $L_{p,\mathrm{OA}}$ and angle	Min $L_{p,\mathrm{OA}}$ and angle	Average $L_{p,\mathrm{OA}}$
90°-50°	193.7 dB at 88.0°	190.6 dB at 81.6°	191.7 dB
50°-30°	192.4 dB at 43.2°	190.3 dB at 39.9°	191.6 dB
30°-0°	195.1 dB at 12.0°	192.6 dB at 0.9°	193.8 dB

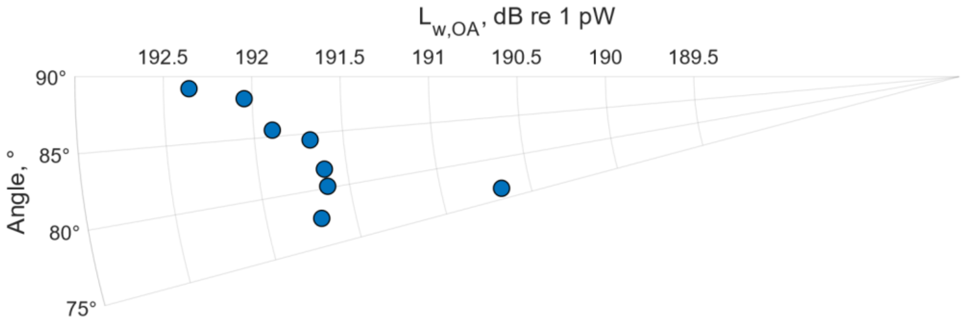

Figure 10. The sound power calculated at the eight microphone locations present at Site 16. Angle is the azimuth relative to the rocket.

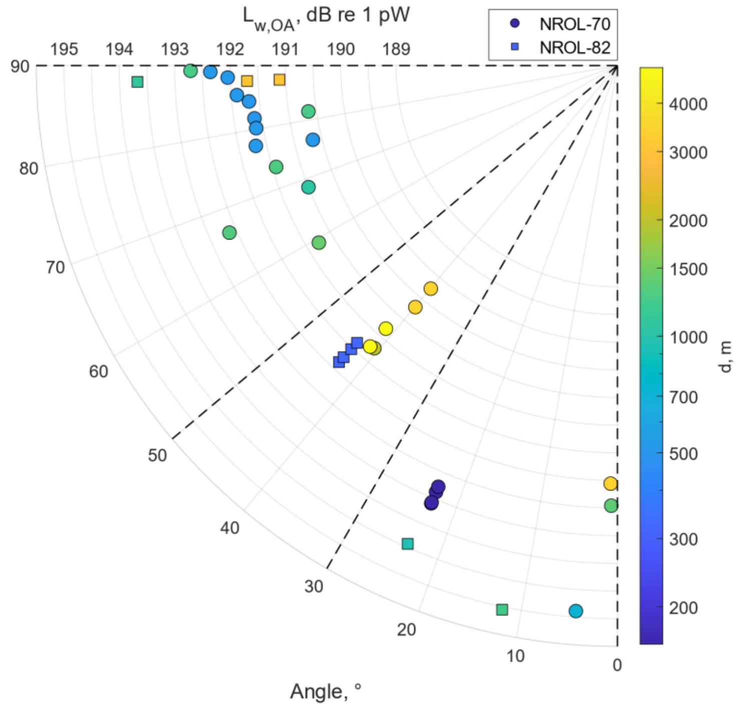

Figure 11. Sound power calculated for 34 measurements relative to the jet midplane (0°) and collapsed to a single quadrant. Circle markers represent measurements from the NROL-70 launch, while square markers represent NROL-82. The color of the marker indicates the distance from the launch pad in meters. Dashed lines show the angular divisions used for further analysis.

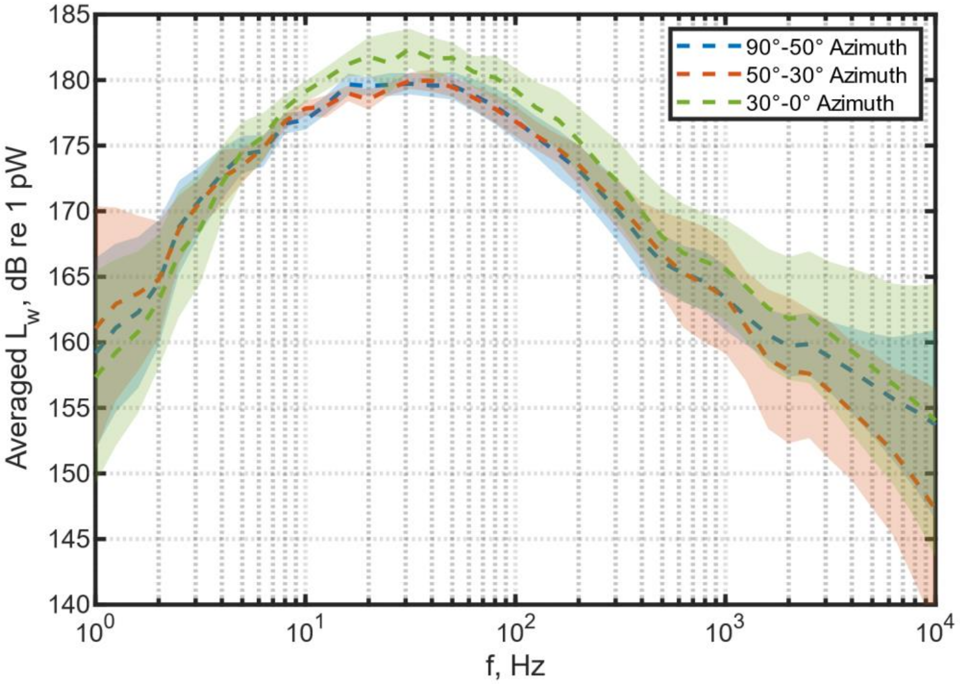

Figure 12. **Decibel-averaged L_w for the 90°-50°, 50°-30°, and 30°-0° azimuths. Dotted lines represent the mean of each angular region; shaded regions represent ± 1 standard deviation from the mean.**

VI. Conclusions & Future Work

This study presented results from two measurement campaigns of the Delta IV Heavy rocket, NROL-82 (2021) and NROL-70 (2024), with the latter specifically designed to investigate azimuthal asymmetry in the radiated acoustic field. Measurements spanning a wide range of azimuthal angles and distances were used to characterize how the three-core configuration influences far-field noise radiation. Initial verification of the dataset was performed through inspection of the pressure-time waveforms recorded at each measurement location. These waveforms exhibited the expected rise in amplitude during liftoff without evidence of clipping or instrumentation artifacts, confirming data quality. Further analysis using running overall sound pressure level and maximum one-third octave spectra revealed clear azimuthal variation. Measurements near the jet midplane showed increases of up to approximately 5 dB in $L_{p,\mathrm{OA}}$ relative to measurements near the jet plane. Spectral comparisons indicated that this increase was concentrated primarily in the low-frequency range, particularly near the peak frequency of approximately 30 Hz. This behavior suggests that large-scale turbulent structures, which dominate low-frequency radiation, are strongly influenced by plume interaction and viewing angle.

To better understand the effective source characteristics, a Strouhal number analysis was performed using multiple definitions of effective diameter. The results demonstrated that neither the single-plume assumption nor the fully merged plume assumption adequately described the observed spectral peak. Instead, agreement with expected Strouhal scaling for large rocket plumes was achieved only when using an intermediate effective diameter. This indicates that the three plumes of the Delta IV Heavy operate in a partially merged regime, where the dominant noise-generating structures span multiple plumes but do not fully collapse. This intermediate behavior provides a physical explanation for the observed azimuthal asymmetry, as the degree of plume interaction varies with direction.

Sound power calculations were then used to quantify variation in acoustic output with azimuthal angle. Analysis of microphones at Site 16 showed measurable variation in sound power over a relatively small angular aperture, suggesting the presence of directional effects even over limited ranges. Expanding the analysis to all available measurements and collapsing the data into a single quadrant revealed consistent trends across the dataset. Average sound power levels were elevated in the 30°–0° region relative to the 90°–50° and 50°–30° regions, indicating increased radiation along the jet midplane.

Further insight was obtained by examining decibel-averaged sound power spectra for each angular grouping. The largest increase in sound power along the jet midplane occurred near the peak frequency, where levels were approximately 2.0–2.5 dB higher than those observed at larger azimuthal angles. At lower frequencies, the spectra remained relatively uniform. At higher frequencies, above approximately 30 Hz, the spectra begin to diverge slightly, with differences on the order of 1–2 dB between angular regions. These results reinforce the conclusion that azimuthal asymmetry is both angle- and frequency-dependent, with plume interaction primarily affecting the large-scale turbulent structures responsible for peak acoustic radiation.

Overall, the measured variation in sound power across azimuth was approximately 2.0–2.5 dB, with the highest levels occurring along the jet midplane. This is consistent with partial plume shielding and interaction effects and remains below the theoretical upper bound of 4.8 dB for three completely uncorrelated monopole sources. These findings demonstrate that the Delta IV Heavy does not radiate axisymmetrically and instead produces a directionally dependent acoustic field governed by partially merged plume dynamics. Computational modeling could further improve understanding of these plume dynamics.

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