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Acoustical measurement and analysis of an Atlas V launch

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In September 2021, an Atlas V rocket without solid rocket boosters was launched from Vandenberg Space Force Base, California, carrying the NASA/USGS Landsat 9 satellite. In this launch configuration, the plumes from the RD-180 engine's two nozzles are unobstructed, providing the opportunity to analyze the sound generated by a liquid-fuel rocket engine with an azimuthally asymmetric nozzle geometry. Acoustical data were collected at various locations surrounding the launch pad, ranging from a few hundred meters to several kilometers. This paper discusses an overview of the measurement logistics, maximum overall sound pressure levels at the measurement stations, and an initial analysis of the azimuthal variability of the overall sound pressure level and spectra along two radials. Within the constraints of this measurement, the Atlas V radiation does not appear to be azimuthally asymmetric.

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Figure 1: Several types of rockets with various configurations. From left to right, Falcon 9, Delta IV Heavy, Falcon 9 Heavy. Photo credit: SpaceX, Michael Peterson/USA, SpaceX

1. INTRODUCTION

A. BACKGROUND

As satellites and launch vehicles continue to become cheaper to design, manufacture, and operate, the frequency of launches per year is expected to continue increasing. Early research on launch-generated noise was primarily conducted in the years leading up to the Apollo program.[1-3] Rocket noise is a complicated aspect to model due to many influential variables. The models that were created during the 1960's and 1970's are still used today, with some modifications.[4] These models are mostly empirically based, and the underlying physics is still largely unknown. The high-intensity noise radiated by rockets has potential negative impacts from payload damage and structural fatigue to unknown environmental effects. Due to these potential impacts, a more complete understanding of rocket noise is needed to mitigate these issues. A concerning aspect of the generated noise is the high amplitude pressures created by the exhaust flow. These pressures create shock content and become nonlinear.

Current rockets come in a diverse set of shapes and sizes, which adds to the complexity of modeling noise. Notably, the nozzle configurations can vary substantially from rocket to rocket. As Figure 1 shows, the numbers of nozzles or boosters is variable across designs. The shapes and sizes of the nozzles directly augment the sound produced. Some rockets are designed such that the configuration is adaptable to the specifications for a specific mission set. The current acoustic effects of multiple-nozzle engines and multi-engine launch vehicles are, as of yet, inconclusive due to the lack of research that has been done.

B. AZIMUTHAL ASYMMETRY

Differing nozzle geometries may have notable impacts on the sound field produced by a jet, as indicated by studies done by Kantola[5] and Bozak[6]. As these studies have found, at significant spacings between twin jets, or twin nozzles, shifts in overall sound pressure level (OASPL) and spectra have been documented in certain directions. These shifts appeared only at certain azimuthal angles from the rocket. At some angles, the shift was not evident. The difference between shielded and unshielded regions show that the directivity of the sound could be regulated to best fit the launch sites by orienting the rocket to the angle where sensitive areas are experiencing the downward shift in OASPL. In areas where the plume exhausts shield each other, the sound pressure level can be lowered by 1-2 dB. This lower level should be most distinct around the maximum OASPL. These effects were seen at angles where one exhaust plume blocked the other.

The remainder of this paper analyzes the sound levels produced by the Atlas V rocket (Figure 2). The paper is organized as follows. The experimental design section discusses the specifics of the launch and the anticipated results. The results section shows the OASPL and the spectra along radials where acoustic shielding should be noticeable. The conclusion then compiles the results and reports significant values for further research.

Figure 2: Launch of the Atlas V 401 rocket as part of the Landsat 9 mission out of Vandenberg Space Force Base, California. Photo credit: NASA/Kim Shiflett

2. MEASUREMENT DESIGN

A. ATLAS V

The rocket studied was the Atlas V from the NASA Landsat 9 launch, seen in Figure 2. Vehicle specifications can greatly impact the generated noise. The vehicle was in a 401 configuration, meaning that it has a single engine and no solid rocket boosters, giving it a nominal thrust of about 3.9 MN. The engine used in the first stage is the Energomash RD-180 where the exhaust exits from two 1.4 m diameter nozzles. By photo analysis, the nozzles have an approximate throat separation of 1.7 m. The spacing between nozzles over the diameter of the nozzle, s/D , is a useful ratio to use when comparing between vehicles. A potentially useful model when considering multiple nozzles is to consider them as a single nozzle with an effective exit diameter. This effective exit diameter, D_{eff}, is the same as a single nozzle with the same combined area as the two separate nozzles. With two nozzles, $D_{eff} = D\sqrt{2}$, where D is the exit diameter of one nozzle.[1] Using the diameter as 1.4 m in the spacing ratio, the value is 1.21.

The exit velocity of the exhaust coming from the engines affects the generation of the noise by turbulent mixing with the ambient air. The Mach number is used to convey the speed of the vehicle relative to the speed of sound in the ambient air. The Oertel convective Mach number[7] is often useful in comparing different rocket plumes and their directivities.[8-9] This parameter considers the fully expanded jet velocity, the speed of sound at the exit for the fully expanded condition, and the ambient speed of sound. These measurements depend on the engine parameters of each vehicle. The calculated Oertel convective Mach number for the Atlas V is approximately 3.1 given these conditions. This convective Mach number is substantially larger than that for solid rocket boosters[10], which have a convective Mach number of around 2.3. Study of the Atlas V directivity and its relation to the Mach number may be the study of future work.

Figure 3: Locations of measurement stations with maximum OASPL values and distance from the launch site(SLC-3). The different radials are highlighted.

B. MEASUREMENT DETAILS

The Landsat 9 Atlas V mission launched from Vandenberg Space Force Base (VSFB) Space Launch Complex 3 (SLC-3). The microphones were situated around the launch pad as shown in Figure 3. The plan was to collect data along the axes of the nozzles as seen in Figure 4, giving a 90° difference. These radials were oriented relative to the launch building. However, the vehicle was rotated relative to the building, and so the set-up locations were offset by about 25° from the desired radial directions. The yellow radial goes through Stations 4 and 5. This is the 25° radial, meaning that the two rocket nozzles are mostly in-line with each other and only one of them can be seen from this perspective. The green radial that goes through Stations 1 through 3 is therefore the 115° radial. Both nozzles can be seen from this radial. Given the vehicle axes of symmetry, the sound radiation at 115° should be the same as 65°. Two arcs are analyzed along these radials: one at 500 m (Stations 1 and 4) and 1400 m (Stations 2 and 5). The differences between these arcs only give an effective difference of 40° due to symmetry, assuming that the noise is spherically propagating. Ideally a 90° difference would best showcase the azimuthal asymmetry of the vehicle but given this small difference, this angle may not be large enough for shielding to occur.

At each measurement site, an inverted microphone was placed above a plastic circular ground plate under a 1.5 in thick dome windscreen[11]. An example of this type of setup is shown in Figure 5. Depending on location, the microphones used were either 12.7 mm (0.5 in) or 6.35 mm (0.25 in) diameter GRAS microphones, with the data sampled at either 102.4 kHz or 51.2 kHz.

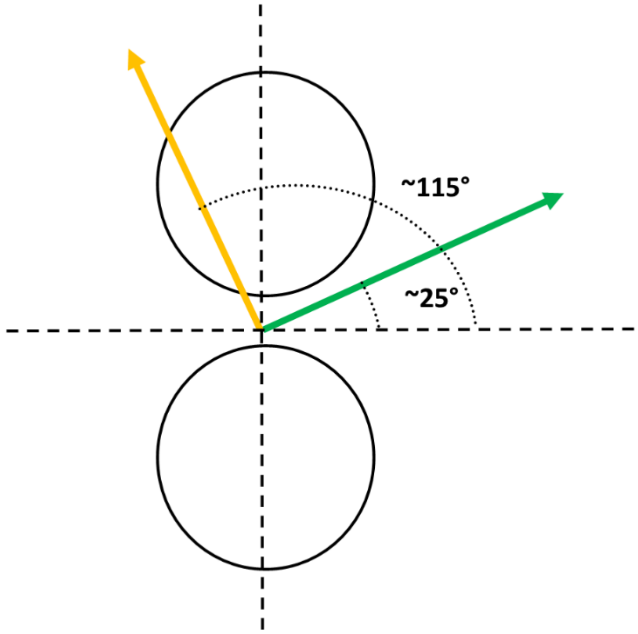


Figure 4: Diagram of the measurement angles with respect to the engine nozzles.

If acoustic shielding occurs between the plumes, a 1-2 dB drop in OASPL should be observed. In the frequency domain, around a 3 dB difference should be seen beginning around the peak frequency and continuing off into the high frequencies, as found in previous studies[5,6]. This should be seen at the 90° and 0° angles relative to the nozzles. Since the measurement was shifted by about 25°, effects due to acoustic shielding are not expected to be prominent in the OASPL and spectral shifts. These studies[5-6] have shown the OASPL and spectra shifts are mostly impacted by the spacing between the nozzles.

Figure 5: Example setup of Station 1. Included: a PUMA case(brown), COUGAR housing of the microphone shown by the black windscreen, and solar panel for independency.

3. RESULTS

A. SOUND LEVEL

If there is an azimuthal difference between the two radials, it should be seen in a comparison of the OASPL along both radials. The previous work suggests that there should be a 1-2 dB drop in maximum OASPL with a 90° difference between measurements. Figure 5 shows the comparisons of the azimuthal stations at 500 m and 1400 m. Since the maximum in OASPL is where the difference is expected, the plots from each station are maximum aligned, as shown in Figure 6. The maxima on the 500 m radius are 138.2 dB and 137.6 dB with the green radial being higher. The peaks on the 1400 m radius are 126.4 dB and 125.9 dB with the green radial again being higher. Other studies have reported larger s/D values which means that the expected difference should be even less than 1-2 dB.[6] There is also a smaller azimuthal difference between these data which would also decrease the expectations of 1-2 dB. This leads to the conclusion that a half a dB difference between radials is not thought to be significant enough to attribute to acoustic shielding.

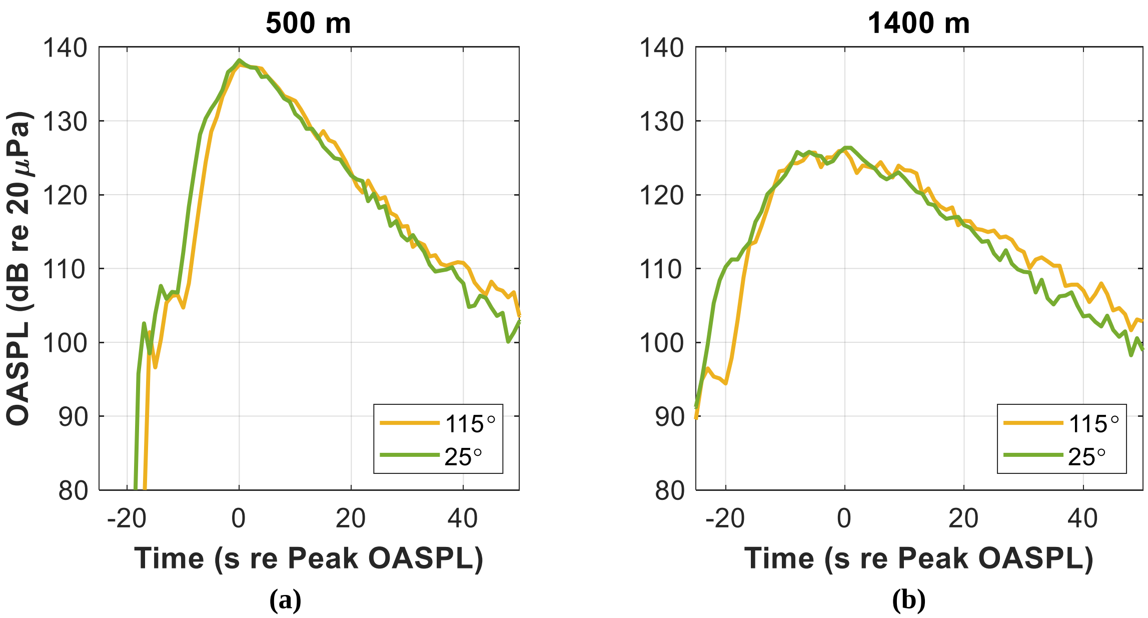
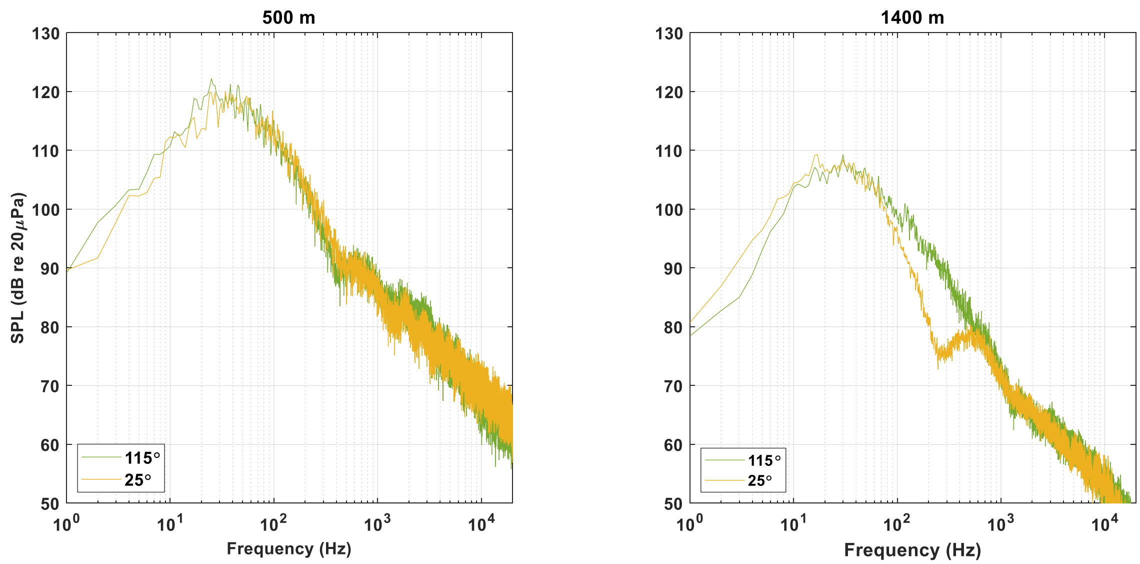


Figure 6: Peak aligned OASPL of each station along the 115° and 25° radials

B. SPECTRA

There is still the possibility that there is some azimuthal variability in the spectrum, even if the OASPL is not different. The spectra were calculated between the 3-dB-down points at the maximum of the recording. The spectral effects that should be seen due to shielding were found to be around a 3 dB difference starting at the peak frequency and continuing towards high frequencies. Figure 6 compares the spectra along the radial at 500 m and 1400 m. Both radials follow the same trend at high frequencies. At low frequencies along the two radials, there is no consistent trend that one angle has a higher SPL than the other. Both radii peak around 30 Hz. This frequency value will be used for the Strouhal number calculations.

The spectra on the radii should appear to be the same before the peak frequency and have a distinct difference afterwards. As Figure 6 shows, there is no discernible difference between the signals other than a null at the 1400 m radius around 400 Hz. This null does not seem likely to be due to azimuthal dependence, but rather appears to be some sort of atmospheric effect on the propagating sound. Since the microphone is essentially ground-mounted, it cannot be a ground-reflection effect at that frequency range, and there was nothing near the microphone that could cause destructive interference. At the time of the maximum OASPL the rocket was about 300 m above the ground and entering a layer of clouds above the launch site, which could account for the dip in sound pressure level. A similar frequency null at a lower frequency was also documented during measurements of the Space Launch System's Artemis-I launch. Due to the similar nulls across different measurements suggests that there is some type of meteorological effect that is still unknown.[12]



(a) (b)

Figure 6: a) Spectra along the 500 m radius comparing azimuthal angles. b) Spectra along the 1400 m radius comparing azimuthal angles.

C. STROUHAL NUMBER

The Strouhal number is a useful metric when comparing noise generated by jet flow. It is a nondimensional number that is used to collapse jet-based noise to fit a collective model. This number has mostly been used for jets[5,6], but is also relevant for rockets[9] due to the similar generations of noise. This metric relies on inherent properties of the rocket exhaust plume. The Strouhal number was calculated using the peak frequency value, found in Figure 6, of 30 Hz. Using this frequency value, the Strouhal number was calculated using four different formulations. These methods have been heavily discussed in other papers and the most universal or appropriate scaling is still unknown[8,9]. Each value is compared to the same calculations that were done on the Falcon 9 vehicle as shown in Table 1. This vehicle is treated as azimuthally symmetric given its nozzle configuration, despite having 9 engines. The values in Table 1 are shown using an effective diameter. When comparing the Strouhal number between the two vehicles, the values are very similar. This could be further evidence of a rapid merging of the plumes and not having any acoustic shielding.

STROUHAL FORMULATION	Sr (D_{eff}) ATLAS V	Sr (D_{eff}) FALCON 9 [MATHEWS ET AL.][6]
$\frac{f_{pk}D_{eff}}{U_e}$ (ELDRED)[1]	0.018	0.019
$\frac{f_{pk}D_{eff}}{c_e}$ (COLE ET AL.)[2]	0.070	0.064
$\frac{f_{pk}D_{eff}}{c_a}$ (GRESKA ET AL.)[7]	0.175	0.170
$\frac{f_{pk}D_c}{c_a}$ (POTTER AND CROCKER)[13]	0.355	0.250

Table 1: Strouhal number comparisons between the Atlas V and Falcon 9 launch vehicles. See Mathews (2021)[8] for variable and equation definitions.

The reported Strouhal number is 0.355 using the last formulation shown in Table 1. These values are used for frequency comparisons between launch vehicles with varied engine specifications. To determine which formulation is better suited for the Atlas V a closer look into the formulations is required. The variation between 0.250 for the Falcon 9 and 0.355 for the Atlas V is less than 1 octave when using the Potter and Crocker formulation. Looking at the Eldred formulation, Tam (1995)[14] suggests that the peak Strouhal number in the max radiation direction for a supersonic jet is between 0.1-0.3. This range is largely different from the calculated value of 0.018, suggesting that there is need for further study for these formulations. The Reusable Solid Rocket Motor (RSRM) was found to have a Strouhal number with the Potter and Crocker formulation of 0.4 which correlates well with the values calculated for the Falcon 9 and Atlas V. As suggested in previous studies[6-7], the Potter and Crocker formulations produce the most favorable results in scaling parameters to different jet types.

4. CONCLUSION

This paper has described acoustical measurements of the United Launch Alliance Atlas V, as made during the NASA Landsat 9 mission. The results suggest that the Atlas V's first stage RD-180 engine nozzles can be modeled as a single plume with an effective nozzle exit diameter because none of the expected shifts due to acoustic shielding are observed. Using this model on other rockets of similar nozzle spacing will increase the accuracy of the results given by other acoustical analyses. Given that the peak frequency was found to be 30 Hz, varying formulations of Strouhal number were calculated. All of these formulations correlated closely with the other values for the Falcon 9. All of these values were within an octave showing that each one is comparable to either rocket.

There was no evidence seen in the spectrum or OASPL for azimuthal variability in the Atlas V rocket. This could be due to the data not being collected exactly along the 0° and 90° radials and there being only a 40° difference between the stations. Since the values are very close together from the 25° and 115° radials, the shifts are expected to be small if at all noticeable, and the 0.5 dB difference that is seen is not significant enough to show the shielding effects. Therefore, the Atlas V most likely cannot be oriented in such a way to direct the more intense sound towards less acoustically sensitive areas.

The spacing between the nozzles and s/D ratio, is small enough that large acoustic shielding effects are not expected. These expectations were confirmed as none of the potential effects were observed. This would be due to the exhaust from the nozzles combining early enough into a single plume, which happens with a small s/D value. As seen in previous work there must be a considerable distance between nozzles for shielding to have a large enough impact in the perceived levels.

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REFERENCES

[1] Eldred, K. M. (1971). "Acoustic loads generated by the propulsion system (No. NASA SP-8072)." National Aeronautics and Space Administration.

[2] J. Cole, H. Von Gierke, D. Kyrasis, K. M. Eldred, and A. Humphrey. (1957). "Noise radiation from fourteen types of rockets in the 1,000 to 130,000 pounds thrust range. Wright Air Development Center (WADC) Technical Report 57-354.

[3] W. H. Mayes, W. E. Lanford, H. H. Hubbard. (1959). "Near-field and far-field noise surveys of solid-fuel rocket engines for a range of nozzle exit pressures." Washington, DC: NASA TN D-21.

[4] Haynes, J., and Kenny, R. J. (2009). "Modifications to the NASA SP-8072 distributed source method II for Ares I lift-off environment predictions," AIAA Paper 2009-3160.

[5] Kantola, R.A. (1981). "Acoustic Properties of Heated Twin Jets." Journal of Sound and Vibration 79(1), 79-106.

[6] Bozak, R. (2014). "Twin Jet Effects on Noise of Round and Rectangular Jets: Experiment and Model." 20th AIAA/CEAS Aeroacoustics Conference.

[7] B. Greska, A. Krothapalli, W. C. Horne, and N. Burnside, "A Near-Field Study of High Temperature Supersonic Jets," in Proceedings of the 14th AIAA/CEAS Aeroacoustics Conference (29th AIAA Aeroacoustics Conference), Vancouver, BC (May 5–7, 2008), AIAA 2008-3026.

[8] Mathews, L. T., Gee, K. L., and Hart, G. W. (2021). " Characterization of Falcon 9 launch vehicle noise from far-field measurements," J. Acoust. Soc. Am. 150, 620–633.

[9] Lubert, C.P., Gee, K.L., and Tsutsumi, S. (2022)"Supersonic jet noise from launch vehicles: 50 years since NASA SP-8072", The Journal of the Acoustical Society of America 151, 752-791

[10] Bassett, M. S., Gee, K. L., Hart, G. W., Mathews, L.T., Rasband, R. D., and Novakovich, D. J. (2019)"Peak directivity analysis of far-field acoustical measurements during three GEM 63 static firings", Proc. Mtgs. Acoust. 39, 040004

[11] Anderson, M. C., Gee, K. L., Novakovich, D. J., Rasband, R. D., Mathews, L. T., Durrant, J. T., and Leete, K. M. (2022) "High-fidelity sonic boom measurements using weather-robust measurement equipment." Proceedings of Meetings on Acoustics, Vol. 39

[12] Gee, K. L., Hart, G. W., Cunningham, C. F., Anderson, M. C., Bassett, M. S., Mathews, L. T., Durrant, J. T., Moats, L. T., Coyle, W. L., Kellison, M. S., and Kuffskie, M. J. (2023) "Space Launch System acoustic: Far-field noise measurements of the Artemis-I launch." J. Acoust. Soc. Am. JASA-Express Letter

[13] R. C. Potter and M. J. Crocker, "Acoustic prediction methods for rocket engines, including the effects of clustered engines and deflected exhaust flow," NASA-CR-566 (George C. Marshall Space Flight Center, National Aeronautics and Space Administration, Huntsville, AL, 1966).

[14] Tam, C. K. W. (1995). "Supersonic jet noise," Annu. Rev. Fluid Mech. 27, 17–43