

NON-GAUSSIAN ACOUSTIC PRESSURE AMPLITUDES
IN HIGH-INTENSITY SOUND FIELDS
Revision C

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This is a work in progress.

The following discussion refers to sound propagating through air. The sound pressure levels are referenced to 20 micro Pascals.



Figure 1. XCOR Aerospace, Liquid Oxygen/Methane Rocket Engine, Test Firing

Shock cells form in the plume core.

Introduction

The purpose of this paper is to consider acoustic waveforms where the time history and its corresponding histogram, or equivalent probability density function, are skewed¹, and thus non-Gaussian. Such cases are sometimes referred to as “one-sided.”

Consider a supersonic rocket exhaust plume. The sound sources are

1. Turbulent eddies form along the interface between the plume and the surrounding ambient air. The eddies themselves propagate at a supersonic velocity which is very roughly 80% of the jet exhaust velocity. The eddies generate shock waves as shown in Appendix A.
2. Turbulent mixing the wake of the potential core, as shown in Appendix B.
3. Supersonic exhaust jets are imperfectly expanded, or “choked.” They contain shock cells through which the flow repeatedly expands and contracts. The cells form a pattern inside the jet which appears as a series of diamonds, as shown in Figure 1 and in Appendix B.

Shock waves are the dominant source of sound radiation. The shock waves are also referred to as *Mach waves*.

Crackle is a special case of pressure shock waves where the skewness exceeds 0.3.

The resulting pressure time histories are thus skewed due to the physics of the shock waves.

Measurement Distortion

Distortion due to inadequate low-frequency response in the measurement system may also play a role in recorded high-intensity sound, as briefly discussed later in this paper.

Furthermore, this error source was recognized by Ffowcs Williams in Reference 1, but he was able to overcome it by using recording equipment with a flat low frequency response.

¹ Note that the statistical definition of skewness is the “third central moment of the probability distribution normalized by the standard deviation.”

Ffowcs Williams Research

Ffowcs Williams described the sound of skewed waveforms from jet noise as *crackle*.

He noted that

1. The crackling of a large jet engine is caused by groups of sharp compressions in association with gradual expansion².
2. Cackle is formed because of local shock formations due to nonlinear wave steepening at the source rather than from long-term nonlinear propagation.
3. Crackling results in distinct bursts of strong narrow positive pressure transients in the time domain.
4. Crackling is not apparent in frequency domain spectral plots.
5. The onset of crackling occurs when the skewness reaches 0.3.

He was concerned about human perception of noise from the Olympus 593 jet engines used in the supersonic Concorde aircraft. Such noise may cause public annoyance and complaints.

But his findings are also useful for characterizing rocket exhaust noise, as given throughout this paper.

High-Intensity Source Levels

The space shuttle liftoff environment is 180 dB at the launch pad. The level is about 159 dB at a distance of 240 feet. These levels are taken from References 2 and 3.

The F-1 rocket engine generated a sound pressure level of 164 dB at 10 inches from the nozzle exit plane, per Reference 4. The Saturn V first stage had five F-1 engines. The overall level for five engines would have been about 171 dB.

The acoustic time histories can be skewed for levels as low as 159 dB, as shown in this paper.

Some Basics

The ambient air pressure at sea level is “one atmosphere,” or approximately 14.7 psi on the absolute scale.

The absolute pressure in a vacuum is zero psi.

The absolute pressure in any volume is thus ≥ 0 psi.

² This has been verified via recording equipment with a flat low frequency response.

Gage pressure is the pressure relative to the atmospheric pressure. Acoustic pressure in the time domain is almost always represented in terms of gage pressure.

The acoustic pressure is thus ≥ -14.7 psi gage.

Maximum Sound Pressure Levels for an Undistorted Wave

Now consider a class of sound pressure time history curves, where each oscillates symmetrically about the zero baseline in terms of gage pressure. Furthermore, consider the special case of a hypothetical (but unrealistic) rectangular wave where the peak and the RMS values are the same. The maximum pressure limits for this case would be -14.7 to +14.7 psi. The maximum overall pressure level would be 194.1 dB. This is the theoretical limit for undistorted sound at 1 atmosphere environmental pressure.

Shock Waves

Higher levels are possible for the cases of distorted waveforms where the corresponding histogram is skewed. An example is a shock wave where the waveform valleys are clipped at zero pressure on the absolute scale. But the peaks may be arbitrarily high.

A shockwave may thus have an overall pressure level > 194.1 dB. These waveforms are considered to be pressure waves rather than sound waves, however.

Distorted Sound Waves

The “laws of practical physics” do not allow a sound wave to have a minimum pressure level of zero psi absolute. Various thermodynamic and molecular chemistry effects intervene well before this limit would be reached. An understanding of these effects is a topic for future research.

The philosopher Baruch Spinoza (1632-1677) wrote “Nature abhors a vacuum.”

This observation is particularly true in acoustic fields, where distortion begins at levels as low as 159 dB, or 0.25 psi RMS, as nonlinear restraining mechanisms begin to counteract the forming void.

Molecular friction is a factor. Ffowcs Williams describe crackle as a *rasping fricative* sound.

He also wrote that nonlinear distortion occurs because compressive sections of the wave travel faster than their expansive counterparts.

Plume Impingement Aero-acoustic and Vibration (PIAAV) Test



Figure 2. Solid Rocket Motor, Static Fire Test.

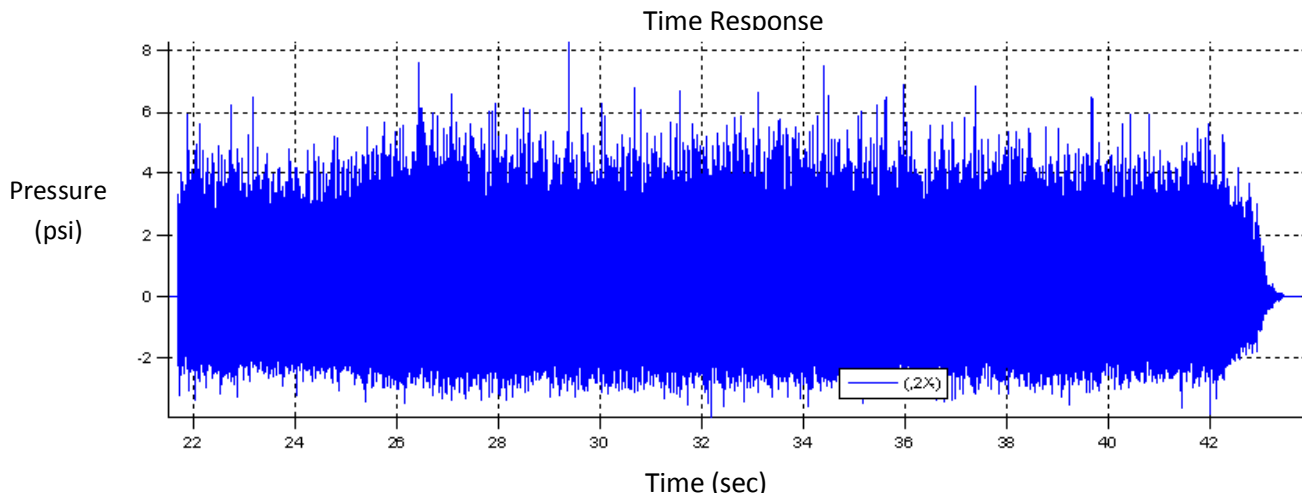


Figure 3.

A 24-inch SRTMV-N1 Solid Rocket is shown in Figure 2. The motor produced 21,500 lb of thrust, with a 21-sec burn time. A 1/8-in steel plate was mounted at the side of the plume. The plate was instrumented with both accelerometers and pressure transducers. The plate was excited by both hydrodynamic and acoustic pressure.

The fluctuating pressure time history from the plate in Figure 3 is skewed. The overall level was 170 dB per Reference 5. The authors of this reference claimed that the skewness was due to real physical effects rather than to instrumentation problems.

Pad Abort 1 Test Configuration

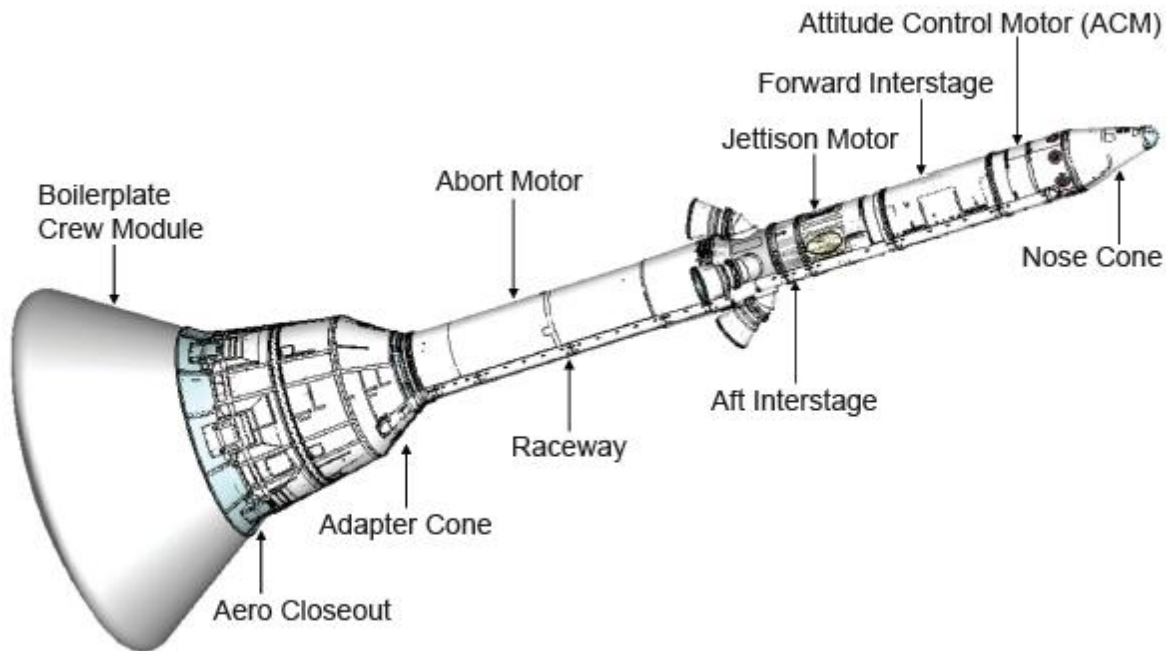


Figure 4.

The purpose of the Launch Abort System (LAS) is to pull the Orion Crew Module and its astronauts safely away from the launch vehicle in the event of an emergency on the launch pad or during ascent.

An unmanned test of this system was performed at White Sands Missile Range, New Mexico, on May 6, 2010.

An acoustic pressure time history measured on the adapter cone is given in Figure 5, as taken from Reference 6. The data was high-pass filtered at 15 Hz due to remove some spurious, low-frequency, instrumentation noise in the raw signal.

The filtered signal is positively skewed, with a skewness of 0.28 for the duration from zero to 3 seconds. Note that the skew value would be zero if the signal had a Gaussian distribution.

SOUND PRESSURE TIME HISTORY LS009V Ascent OML # 32
15 Hz High Pass Filtered

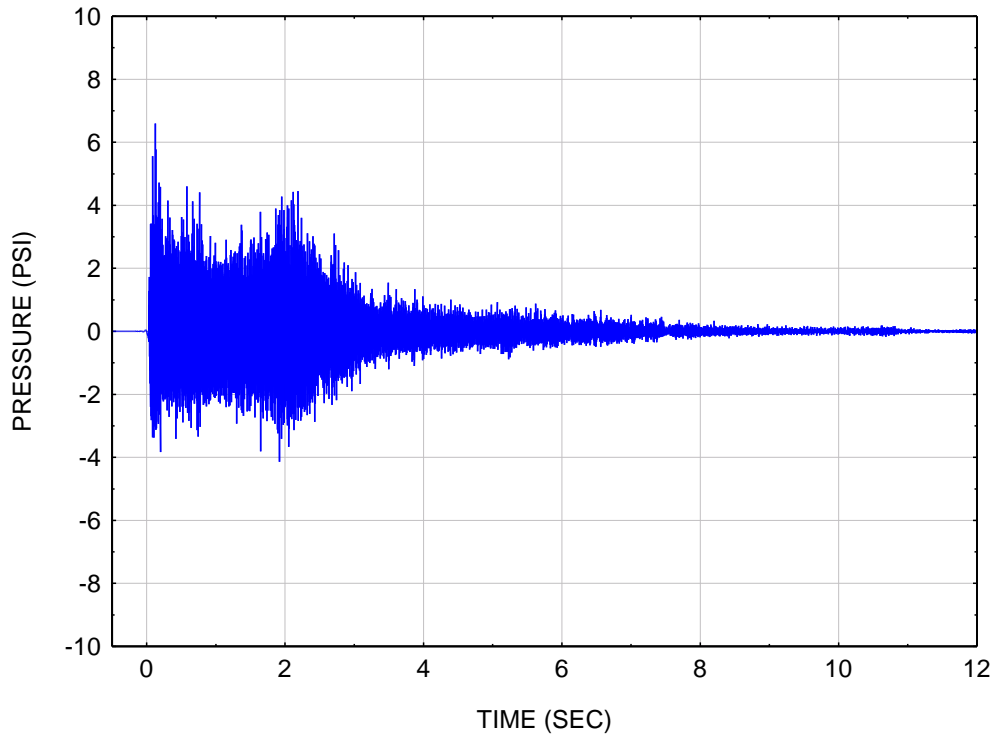


Figure 5.

The following statistics apply to the segment from zero to 3 seconds.

Amplitude Stats

number of points = 19529

mean = -0.00024 std = 1.004 rms = 1.004

max = 6.598 at = 0.1241 sec

min = -4.138 at = 1.918 sec

crest factor = 6.569

skewness = 0.2842 kurtosis = 3.729

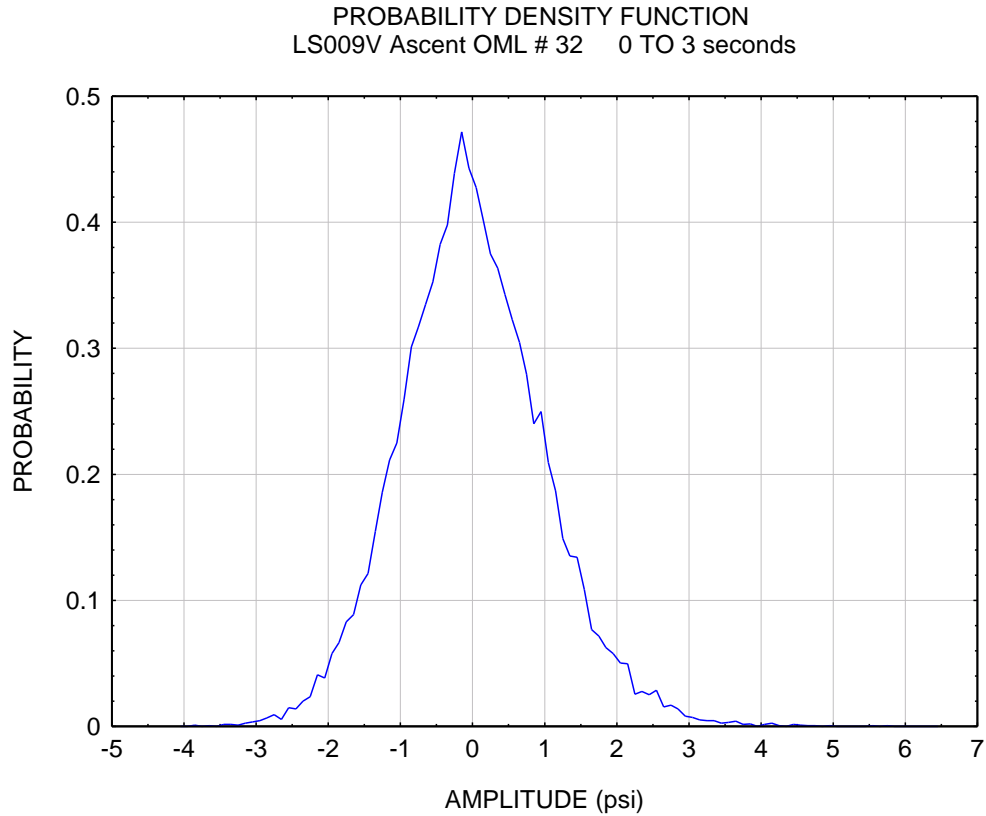


Figure 6.

The probability density function has approximately the same area on either side of the zero amplitude line.

The function is skewed because the peak positive value was 6.598 psi, whereas the peak negative value was -4.138 psi.

The rocket exhaust noise probability density function in Figure 6 is similar to that of crackling jet noise in Reference 1, Figure 3.

ONE-THIRD OCTAVE SOUND PRESSURE LEVEL LS009V Ascent OML # 32
0 to 3 sec OASPL = 171.2 dB Reference = 20 micro Pa

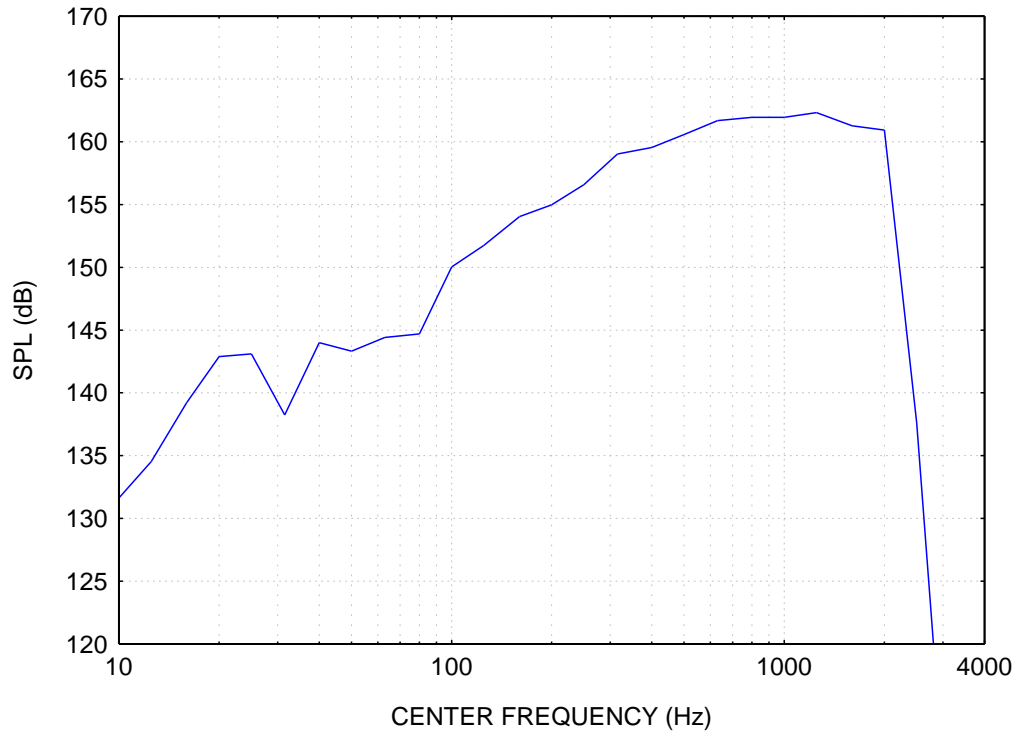


Figure 7.

The sound pressure level was lowpass filtered at 2000 Hz by the onboard instrumentation.

Note that the level was driven by both hydrodynamic plume impingement and acoustic effects.

STS-68 Liftoff Acoustics

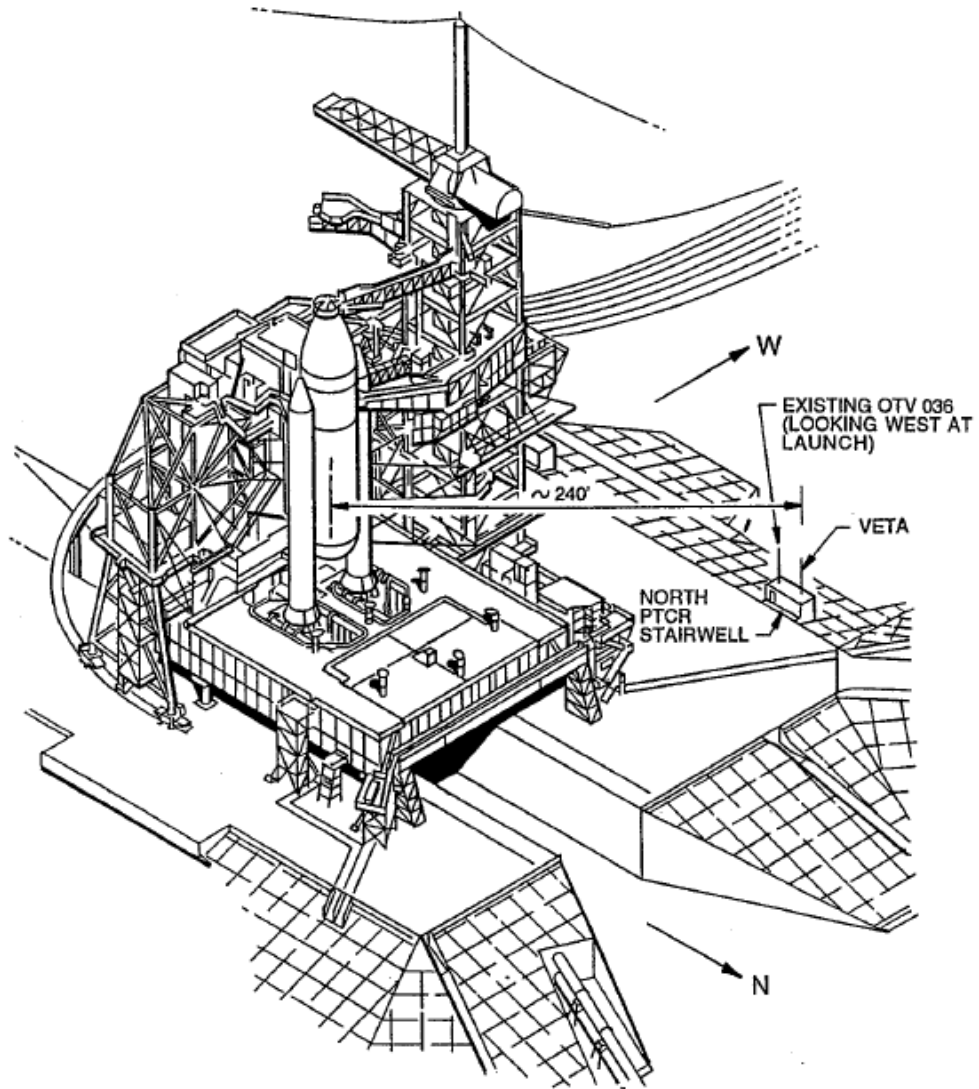


Figure 8. Space Shuttle Launch Pad

The authors of Reference 2 made liftoff sound and vibration measurement on a cantilever beam mounted 240 feet away from the space shuttle. The beam was referred to as the Verification Test Article (VETA).

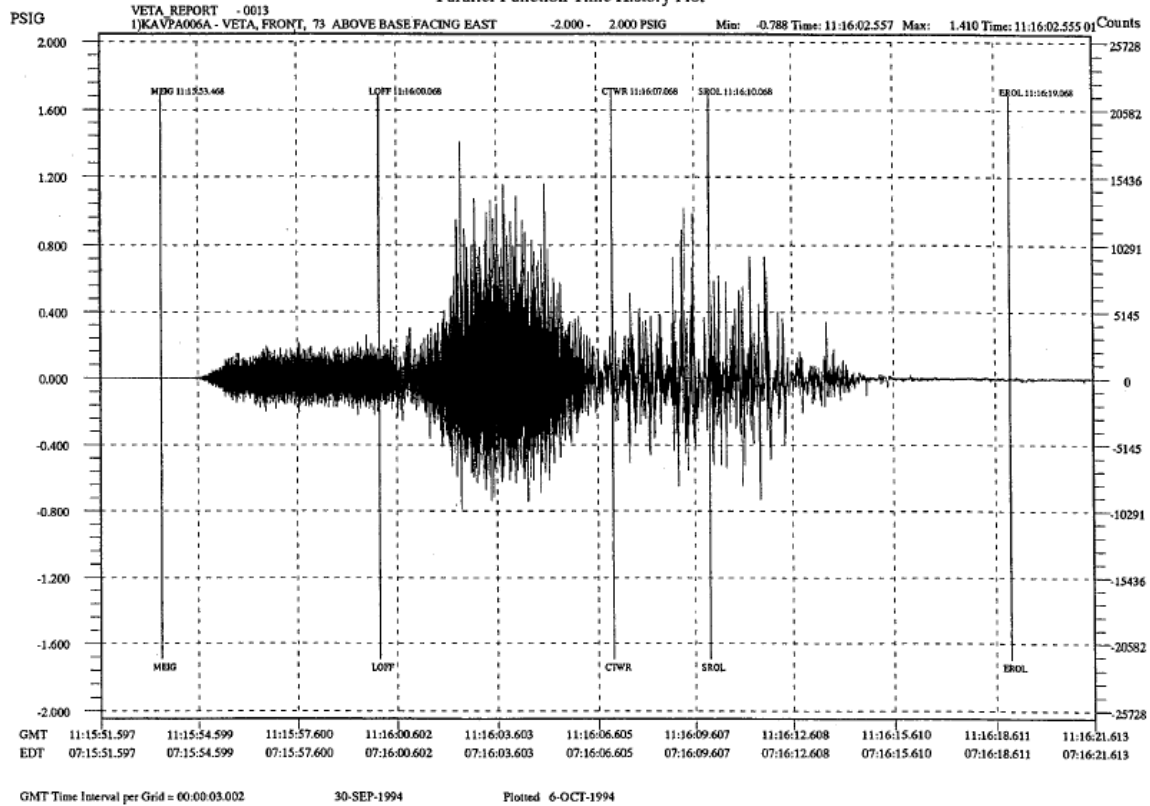


Figure 9. Acoustic Pressure Time History at 240 feet from the Space Shuttle Vehicle, Liftoff

The data is positively skewed during the middle segment.

The time-varying overall level is not given in Reference 3. A rough estimate is that the level was at least 159 dB (0.25 psi RMS) for the segment with the highest peaks, in the middle of the plot. But this level would depend on duration limits.

McInerny's Research

McInerny studied liftoff acoustic data from several rocket vehicles in Reference 7. She found

1. High level rocket noise is rich in shock content and is positively skewed.
2. The measurement system could have low-frequency response limitations which could distort the data.
3. The pressure gradient is less sensitive to low-frequency instrumentation response and is a more sensitive indicator of shock content than the raw pressure time history itself.

Note that the pressure gradient is the first derivative of the pressure with respect to time.

Conclusion

Shock waves in high-intensity acoustic fields create positively skewed pressure time histories.

This behavior is expected from a consideration of physics, although it appears to begin at thresholds that are lower than expected.

The measurement system may have an inadequate low-frequency response which affects the data. For example, the acoustic energy may be accompanied by low-frequency ignition overpressure at levels beyond the linear range of the microphone and data acquisition system.

The potential for measurement system error thus requires consideration.

But either high-pass filtering or McInerny's gradient technique may be used to assess the shock content of a signal even when it contains a spurious offset or drift due to the limitations of the measurement system.

References

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APPENDIX A

Mach Waves from Reference 8

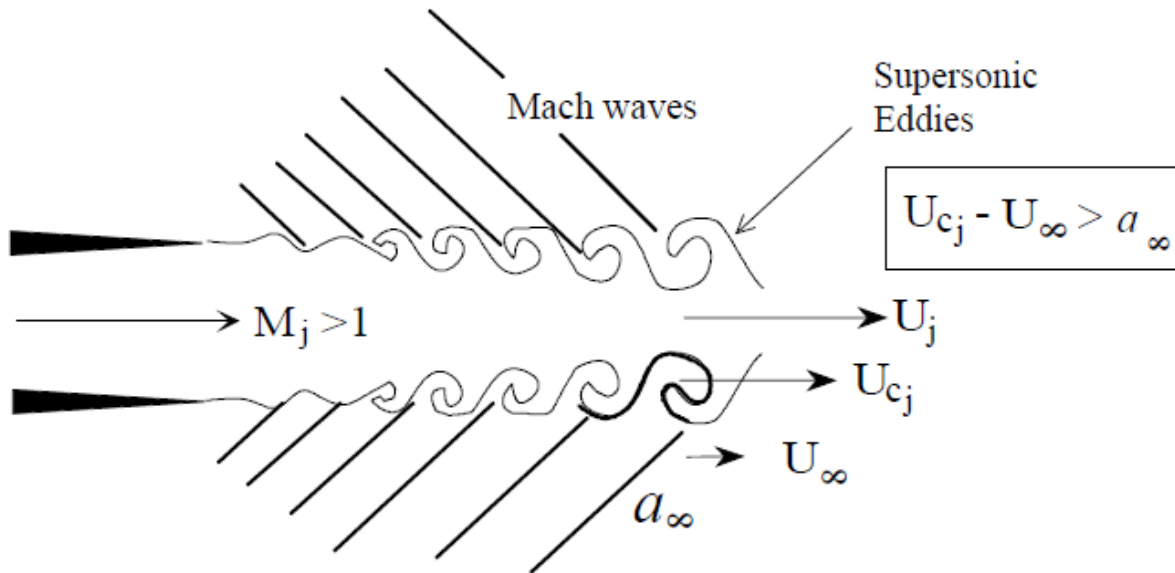


Figure A-1.

Turbulent eddies form along the interface between the plume and the surrounding ambient air. The eddies themselves propagate at a supersonic velocity which is very roughly 80% of the jet exhaust velocity.

Ffowcs Williams wrote that crackle correlates with convecting eddies and is predominant in the Mach wave direction.

He concluded that the resulting pressure spikes are formed because of local convective steepening within the eddying motion.

Exhaust Plume Shock Noise from Reference 11

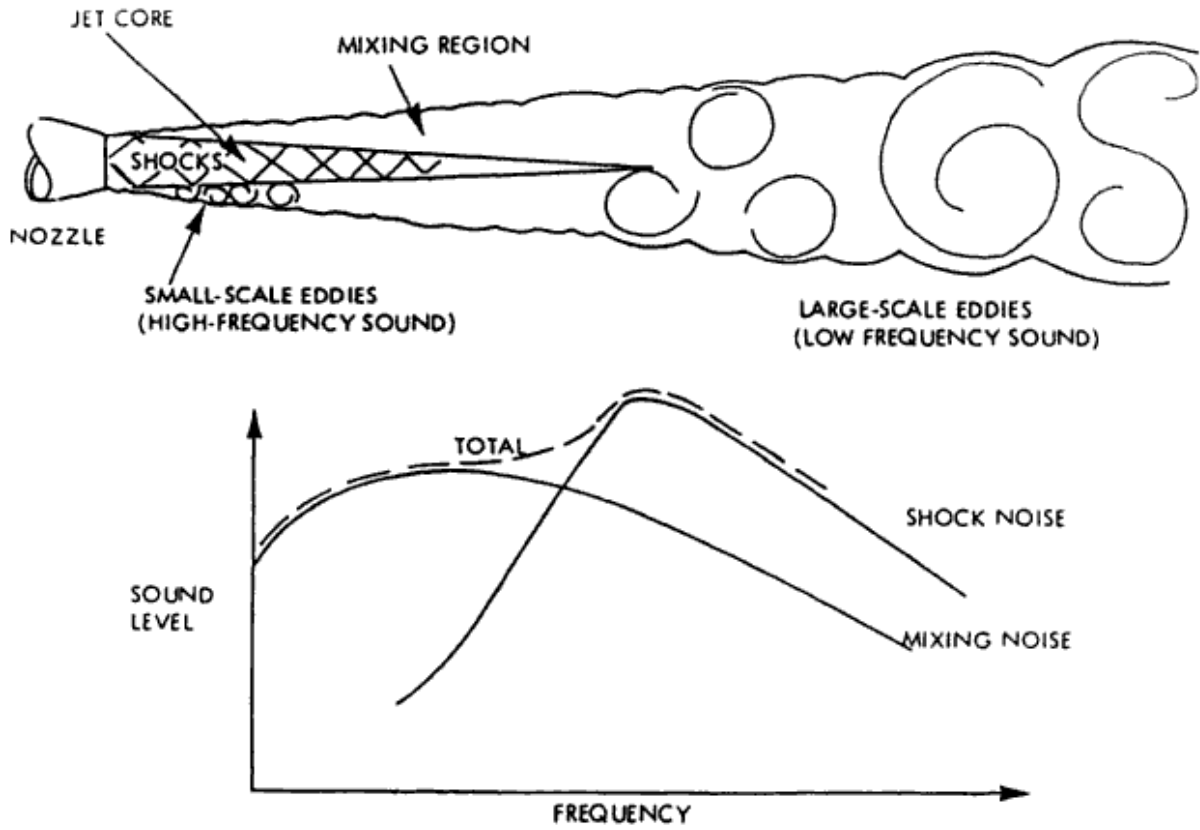


Figure A-2.

APPENDIX B

Excerpt from NASA SP-8072

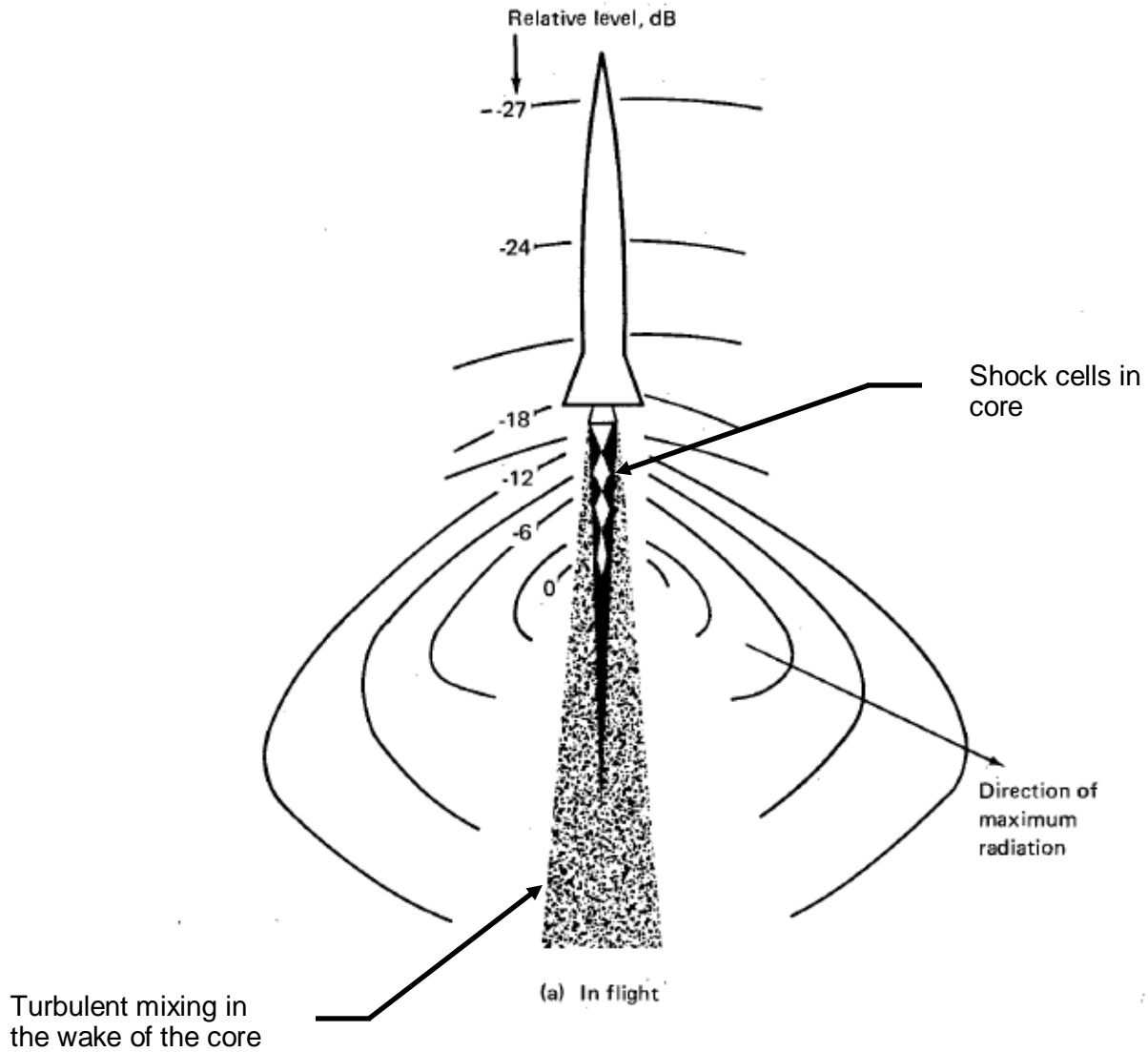


Figure B-1. Noise Sources in an Exhaust Plume during Ascent

The shock cells in the core produce broadband random noise. But they do not emit crackle according to Ffowcs Williams.

See also Beranek, Reference 10.

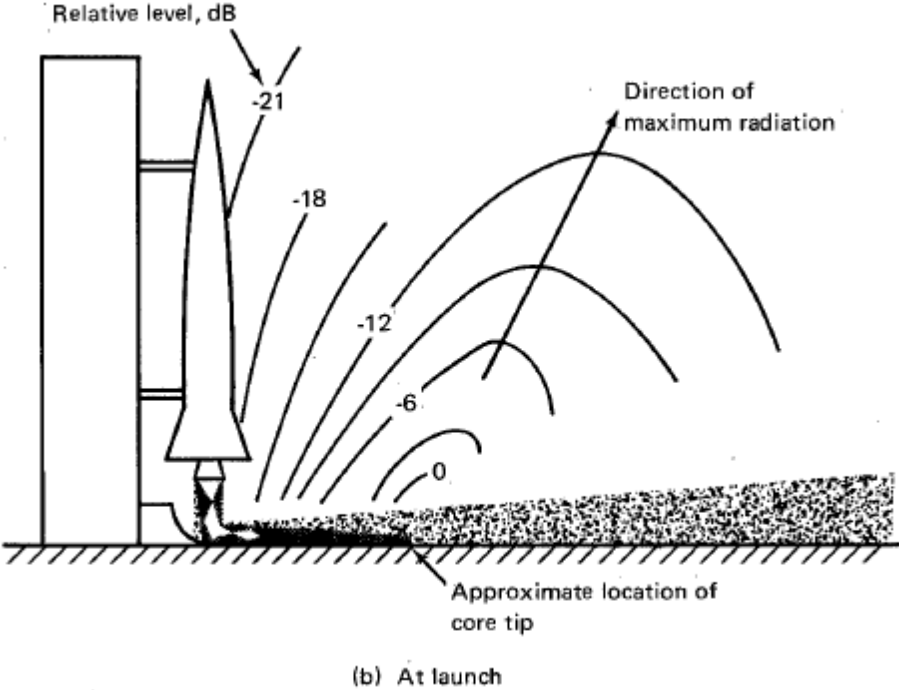


Figure B-2. Noise Sources in an Exhaust Plume during Liftoff