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Sonic Booms from Rockets: Measurements and Modeling

Mark Charles Anderson

A dissertation submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

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ABSTRACT

Sonic Booms from Rockets: Measurements and Modeling

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Rocket sonic booms are produced when launch vehicles or boosters travel faster than the local speed of sound in the atmosphere, generating systems of conical shock waves. The purpose of this dissertation is to perform high-fidelity measurements of rocket sonic booms and to explain the physics behind the unique phenomena observed.

After a thorough literature review on sonic booms produced during spaceflight operations, Part I of this dissertation deals with measurement and analysis challenges. One challenge is reducing contaminating noise effects on sonic boom perception metrics, addressed using a low-pass filtering method tied to the noise floor. A second challenge is analyzing turbulence-induced variability, addressed using measurements across a microphone array along with models and evaluating their agreement. The final chapter in Part I surveys additional sonic boom measurement and analysis methods, including hardware setup and signal processing.

Part II focuses on reusable rocket booster flyback sonic booms, which are produced when a reusable rocket booster descends through the atmosphere to land safely. Two chapters describe field measurements from three flights, showing that the booms do not elongate with distance and that the overpressure plateaus near the landing pad, likely because the booster becomes subsonic several kilometers above the ground. Additionally, the measured flyback sonic boom overpressures exceed launch noise peak pressures for distances greater than 2 km from the landing pad. The next two chapters describe work predicting the unique triple sonic boom waveform also observed in the measurements. Using a combination of theory, nonlinear propagation, computational fluid dynamics, and photographic evidence, the triple sonic boom is shown to result directly from vehicle geometry, without invoking maneuvers or other effects.

Part III examines rocket launch-ascent sonic booms, which can reach communities when launch trajectories are close to the coast. Simulations using NASA's PCBoom software demonstrate that seasonal trends in sonic boom footprints are driven by recurring seasonal weather variations. Subsequent modeling of launch-ascent sonic boom waveforms demonstrates that waveform shapes can be physically explained by the vehicle and plume geometry.

Overall, this dissertation work demonstrates that sonic booms from rockets are an important phenomenon that must be understood as the global launch cadence continues to increase. Moving forward, it will continue to be important to make accurate measurements while simultaneously improving simulation and modeling capabilities to ensure that the physics are fully understood.

Keywords: sonic boom, rocket, nonlinear acoustics, shock wave, acoustics

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Chapter 1

Introduction

In the early days of orbital rocketry, launches were few and fraught with problems, as illustrated in Fig. 1.1. Around the time that the NASA Apollo program started sending astronauts to the moon, the rocket launch cadence stopped increasing and then gradually decreased until the mid-2000s. Around this time, the launch cadence started increasing again and, around 2020, the number of launches per year began increasing dramatically due to growing commercial launch capabilities. In 2025, there were 329 orbital or near-orbital launch attempts around the world (McDowell, 2026).

The total number of launches is not the only thing changing in modern orbital rocketry. Figure 1.2 shows the number of expendable and reusable orbital or near-orbital rockets launched per year through 2025. The reusable vehicles included those with a substantial reusable component either active or planned, including the NASA Space Shuttle, SpaceX Falcon 9, Falcon Heavy, and Starship vehicles, along with relative newcomers like Blue Origin’s New Glenn and the Zhuque-3 and Chang Zheng 12.

The rapidly increasing launch cadence, along with the multitude of reusable launch vehicles being flown or developed, results in additional challenges that must be overcome to enable the sustainable increase of launches around the world. One of these challenges is the noise. While the noise produced by the exhaust gases has been discussed elsewhere (Lubert *et al.*, 2022), this dissertation is focused on a different noise source: rocket sonic booms.

1.1 The Sonic Boom Problem

Any time an object travels faster than the speed of sound, shock waves form in the air surrounding it. These shock waves propagate away from the object and, when observed, are known as a sonic boom. When rockets fly supersonically within the atmosphere, they too produce sonic booms. It is a common misunderstanding that a sonic boom is produced only when the object “breaks the sound barrier”. This is incorrect, as discussed in the thorough review on sonic booms by Maglieri *et al.* (2014). Instead, a sonic boom is generated continuously while the object is supersonic, and an observer on the ground only hears the sonic boom once because the sonic boom only passes over them a single time. This is illustrated in Fig. 1.3, which shows a supersonic aircraft “dragging along”

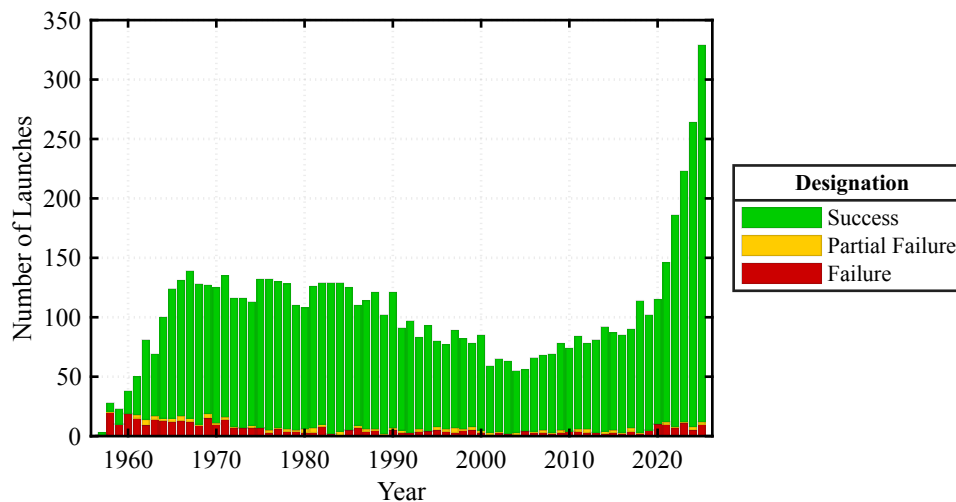


Figure 1.1 The global cadence per year of orbital or near-orbital launches, along with their success rate. Data come from McDowell (2026).

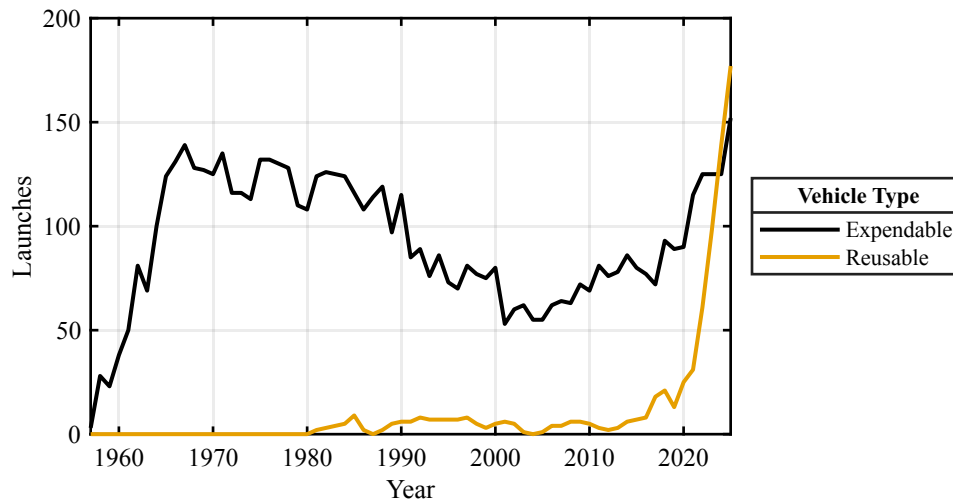


Figure 1.2 The number of expendable versus reusable orbital or near-orbital rocket launches per year as a function of time. Data come from McDowell (2026). Although the launches do not always have a reusable component, all launches of the NASA Space Shuttle, SpaceX Falcon 9, Falcon Heavy, and Starship vehicles, along with Blue Origin's New Glenn and the China Zhuque-3 and Chang Zheng 12 are included.

its Mach cone, which represents the sonic boom. Assuming steady flight, everything that the Mach cone reaches will hear the sonic boom exactly once, though that sonic boom typically consists of two shocks as shown in the upper left-hand side of the figure.

During a rocket launch, there are multiple flight phases that can produce sonic booms on the ground. These phases can be categorized into three distinct categories: ascent, booster flyback, and spacecraft reentry. These are discussed in more detail below.

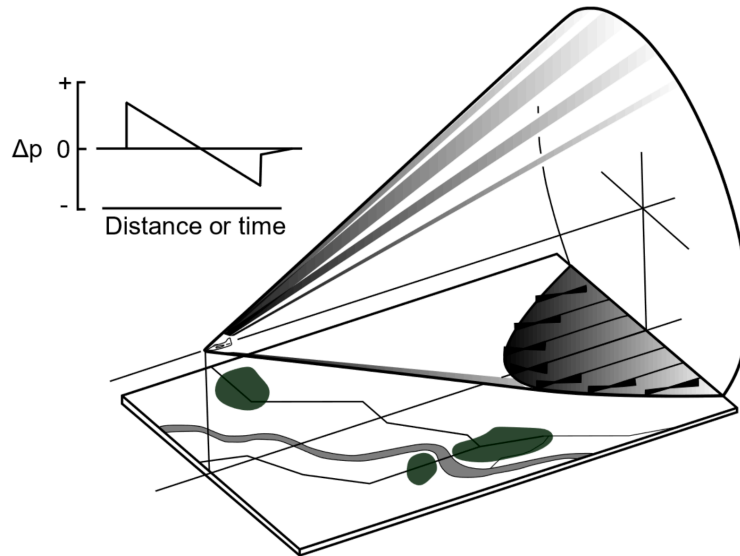


Figure 1.3 A diagram showing a supersonic aircraft and its Mach cone. Reproduced from Lonzaga *et al.* (2022), which is a higher-resolution version than available from the original source (Carlson and Maglieri, 1972). Reprinted with permission from Carlson, H. W., and Maglieri, D. J. (1972). “Review of sonic-boom generation theory and prediction methods,” *J. Acoust. Soc. Am.* 51(2C), 675-685, DOI:10.1121/1.1912901. Copyright 1972, Acoustical Society of America.

1.1.1 Launch Ascent

Although an orbital rocket is typically launched vertically and initially reaches supersonic speeds while traveling predominantly upwards, it must pitch over to reach orbit. If it stayed in vertical flight, then the Mach cone, which forms at some altitude above the ground, would not intersect the ground. However, as it pitches over, the Mach cone rotates and starts intersecting the ground (or water) below. These sonic booms were measured over the ocean during the NASA Apollo (Hilton *et al.*, 1972; Henderson and Hilton, 1974a,b) and Space Shuttle (Stansbery *et al.*, 1983; Stansbery and Stanley, 1984; Garcia *et al.*, 1983b; Stansbery, 1985) programs. They found that the sonic

booms can have high amplitudes on the order of a few pounds per square foot (psf), similar to the Concorde (Loubeau and Page, 2018).¹

More recently, launches from Vandenberg Space Force Base have produced sonic booms on land along the Southern California coast (Green-Lanchoney, 2025, 2026; Gee *et al.*, 2026). While launch-ascent sonic booms have historically occurred primarily over the ocean, rockets have been flying closer to the coast in recent times to use more efficient trajectories for certain orbits, making these sonic booms audible on land.

1.1.2 Booster Flyback

A successful method for reusing a rocket booster is to have it land propulsively. This has been demonstrated hundreds of times with the SpaceX Falcon 9 rocket (SpaceX, 2026). A typical flight profile includes the first-stage booster either returning to land near the launch location or on a downrange floating platform at sea. Other organizations around the world are also developing rockets to fly similar profiles.

As rocket boosters descend through the atmosphere, they reach supersonic speeds and generate a sonic boom. The word “flyback” was chosen to make it clear that the sonic boom is formed while the booster is descending through the atmosphere and not during the subsonic flight immediately before the landing. Before this dissertation work, these sonic booms had only lightly been studied (Durrant *et al.*, 2022a, 2023; Gee *et al.*, 2024b). These sonic booms also have amplitudes on the order of several psf and can be measured at least as far as 25 km from the landing location.

1.1.3 Spacecraft Reentry

Although not the focus of this dissertation, it is important to note a third type of spaceflight-related sonic boom. This is the sonic boom produced when a spacecraft reenters the atmosphere. The Space Shuttle was well-known for its reentry sonic boom, as it often flew over large land masses on its way back to Earth (Garcia *et al.*, 1983a, 1985). Measurements were also made of Apollo capsules returning from the Moon (Hilton *et al.*, 1972; Henderson and Hilton, 1974a). These sonic booms are also an important consideration for future spacecraft as they return from space, especially if flying over land areas.

1.2 Gaps Filled by this Dissertation

This dissertation work is focused on measuring and modeling the sonic booms produced by rockets, especially the launch-ascent and booster-flyback sonic booms. Gaps in the literature and in the understanding of rocket sonic booms have been identified and considerable effort has been devoted to answering questions of both practical and scientific interest. These gaps include questions about proper measurement techniques for sonic booms, gathering data on the sonic booms measured from

¹Conversion: 1 psf = 47.88 Pascals.

modern rockets, and explaining the physics behind the unique sonic boom waveforms produced by rockets. Table 1.1 includes a subset of important questions that are directly answered in this dissertation, along with the chapters where the answers are discussed.

Table 1.1 A sample of the gaps that are filled in this dissertation along with the chapters where they are discussed.

Gap	Chapter(s)
What historical efforts have been made to understand rocket and spacecraft sonic booms?	2
How do you accurately analyze sonic booms in the presence of contaminating noise?	3, 5
How well do the state-of-the-art modeling tools predict the statistics of turbulence-induced variability on sonic boom metrics?	4
How does a rocket booster flyback sonic boom compare to the launch noise?	6, 7
How consistent are rocket booster flyback booms across launches of the same vehicle from the same location?	7
Why does the Falcon 9 rocket booster produce a triple sonic boom instead of a traditional N-wave?	8, 9
Why are rocket ascent sonic booms in Southern California only audible at certain times of year?	10
Why are rocket ascent sonic booms not N-waves?	11

1.3 Dissertation Organization

This dissertation begins with a thorough review of rocket and spacecraft sonic booms in Chapter 2. The literature review is intended to form the basis of a full review article that will be submitted to a peer-reviewed journal after this dissertation is published. This is a service to the global sonic boom community because much of the information discussed in the literature review is buried in reports that have seldom been studied and, in some cases, were not publicly available until specific requests were made as part of this dissertation work.

The remainder of this dissertation is divided into three parts. The three chapters in Part I contain discussions on the challenges of making accurate sonic boom measurements. This work was funded by NASA as part of the X-59 program targeted at developing low-boom technology, though the techniques are directly applicable to rocket sonic booms. These three chapters focus on specific measurement and analysis techniques that have been developed as part of this dissertation work. Additionally, state-of-the-art models were compared with experiments to determine the accuracy expected from simulations.

The four chapters comprising Part II are devoted to reusable rocket booster flyback sonic booms. Chapters 6 and 7 discuss measurements, while Chapters 8 and 9 describe the origin of the triple sonic boom observed during SpaceX Falcon 9 booster flyback events.

The two chapters in Part III are focused on modeling launch-ascent sonic boom phenomena. Chapter 10 demonstrates that seasonal trends in launch-ascent sonic boom footprints are caused by seasonal variations in high-altitude (>15 km) winds. Chapter 11 is then devoted to explaining the origin of the unique blast-wave-like sonic boom waveforms produced by ascending rockets.

Final conclusions and directions for future research are given in Chapter 12. Following this, there are three appendices. Appendix A contains work on determining the sound power produced by a rocket during launch using experimental data. Code documentation and examples are given in Appendix B and the author's contributions to other publications are given in Appendix C.

Chapter 2

The History of Rocket Sonic Booms

This chapter is intended to form the basis of a literature review article on the history of sonic booms produced during spaceflight operations. The interested reader is encouraged to find that review article once it becomes available.

2.1 Introduction

The purpose of this chapter is to outline the historical research performed on rocket sonic booms both on ascent and reentry. Before a meaningful review can be conducted, it is important to first cover some sonic boom fundamentals (Section 2.2), including methods for estimating the pressure signatures near the vehicles and propagating them to the ground. The main portions of this literature review are Sections 2.3 and 2.4 on rocket launch-ascent and spacecraft reentry sonic booms respectively. The vast majority of information in these sections comes from NASA reports. Within these reports, there are many other reports that are referenced but are not publicly available. Where appropriate, those non-publicly-available reports have been referenced herein. Requests have been submitted to make many of these documents available, and a few of them have become available via Freedom of Information Act (FOIA) requests and have started appearing on the public NASA Technical Reports Server (NTRS). Lastly, Section 2.5 contains an overview of responses to sonic booms including structural and human. Because human response in particular is extremely complex and depends largely on psychological factors beyond the scope of this dissertation, only a brief overview of human response will be given.

2.2 Sonic Boom Fundamentals

Whenever an object travels faster than the local speed of sound, it produces shock waves in the surrounding medium. These shock waves propagate away from the object at approximately the speed of sound. This is visualized on the left in Fig. 2.1, where NASA researchers captured the shock waves surrounding an aircraft during supersonic flight. As the shock waves propagate away from the aircraft, they begin to coalesce. Given sufficient propagation distance, the shocks tend to

coalesce into a single front shock and a single rear shock. The final signature looks like a capital “N” and is called an “N-wave”. This process of shock merging is depicted on the right in Fig. 2.1.

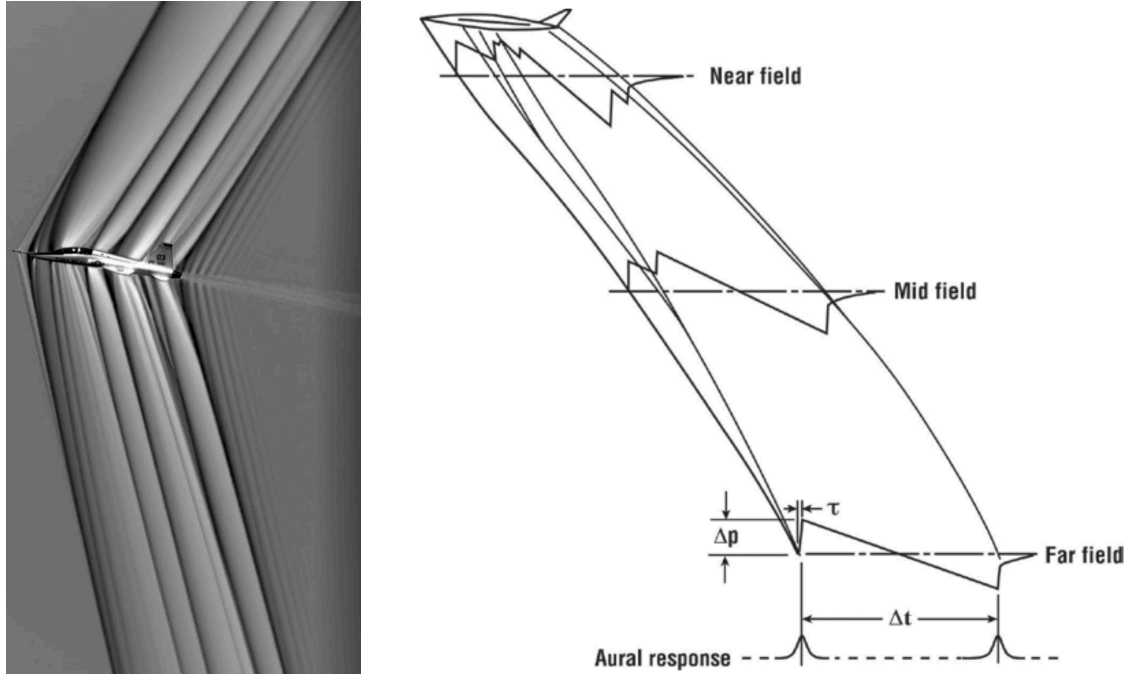


Figure 2.1 (Left) The system of shock waves formed around a supersonic T-38 aircraft. Image credit: NASA (URL: <https://www.nasa.gov/centers-and-facilities/armstrong/nasa-armstrong-advances-shock-wave-photography-2/>, last viewed 02/09/2026). (Right) A schematic depicting the trend for the system of shock waves to coalesce into a front and rear shock, also known as an N-wave. Source: Maglieri *et al.* (2014).

2.2.1 Determining the Near-field Pressures

Sonic boom theory is generally traced back to the paper by Whitham (1952), wherein he described the flow field around any slender, axisymmetric body to first order. This first-order description enabled calculation of shock merging, which in turn enabled accurate sonic boom waveform predictions. At the heart of his theory is the “F-function” typically written today as (Maglieri *et al.*, 2014)

$$F(x) = \frac{1}{2\pi} \int_0^x \frac{A''(\bar{x})}{\sqrt{x - \bar{x}}} d\bar{x}, \quad (2.1)$$

where x is the position along the object, $A(x)$ is the cross-sectional area taken at cuts made at the Mach angle ($\phi = \sin^{-1}(1/M)$, where M is the Mach number), and $\bar{x}$ is an integration variable. If the object is not axisymmetric then the azimuthally-dependent F-function can be generalized to be a function of both x and the azimuthal angle θ . Any object that creates lift will have a different

effective cross-section due to that lift (Walkden, 1958). Thus, the term $A(x)$ can be replaced with an effective area term. For bodies with slope discontinuities, a more general version of the F-function is recommended (Lighthill, 1948; Gottlieb and Ritzel, 1988).

Once the F-function is determined, the near-field pressures at a distance r from the body (propagated linearly) are calculated as

$$\delta p(x - \beta r, \theta) = \frac{p_a \gamma M^2}{\sqrt{2\beta r}} F(x - \beta r, \theta), \quad (2.2)$$

where δp is the change in pressure relative to ambient conditions. A constant value of $x - \beta r$ represents a Mach line.

While there has been much research into the theory of sonic boom generation (see chapter 6 of Maglieri *et al.* (2014) for a thorough review), the near-field pressures can also be determined experimentally by using scaled-down models in wind tunnels. For the case of sonic booms from rockets and spacecraft, examples can be found in Hicks *et al.* (1972b), Hicks and Mendoza (1973b), and Mendoza (1975a) to name a few. More details regarding these methods are given in Sections 2.3 and 2.4.

Additionally, with modern computational resources, computational fluid dynamics (CFD) is another viable method for determining the near-field pressures. A notable example comes from Ashby (1979), where a finite-difference code was validated against wind tunnel data for a reentering Space Shuttle orbiter at Mach 6. Although CFD results have become increasingly prevalent throughout sonic boom studies, a full discussion of these methods is beyond the scope of this review.

2.2.2 Propagation to the Far Field

The first widely-accepted method for propagation of a near-field pressure distribution to the far field for sonic boom prediction comes from Whitham (1952). At the heart of the method are the F-function and theory of characteristics. The shock locations were determined by the area-balancing rule, which could at times be tedious. However, the method was successful and widely used for sonic boom predictions for a few decades.

A theoretically equivalent, but more elegant approach was described by Thomas (1971) and finalized in Thomas (1972). This theory, often referred to as the “Thomas” theory or the “Waveform Parameter Method”, was used heavily after its discovery. The theory consists of breaking the waveform into an arbitrary number of segments, each of which has three waveform parameters associated with it. These parameters are the slope, shock pressure change, and time difference. Using analytical formulas (which are generally solved through numerical methods), these three waveform parameters can be used to describe the waveform evolution all the way to the ground.

While the method of Thomas (1972) was a large step forward, its theory was limited to weak shocks. A separate theory that worked for strong shocks was proposed by Hicks *et al.* (1972b). They recommended using the strong-shock theory in the region where the sonic boom pressures are greater than half of the ambient pressure and then switching to the method of Thomas (1972) once the pressures drop below this threshold.

Modern methods often employ the generalized Burgers equation (GBE), which can be expressed as (Hamilton and Blackstock, 2024)

$$\frac{\partial p}{\partial r} = \frac{\beta}{2\rho_0 c_0^3} \frac{\partial p^2}{\partial \tau} + \bar{\Psi} p - \frac{m}{r} p \quad (2.3)$$

where p is the pressure change relative to ambient, r is the distance from the source, β is the coefficient of nonlinearity ($\beta = 1.21$ in air), ρ_0 is the ambient density, c_0 is the ambient sound speed, τ is the retarded time, $\bar{\Psi}$ is an operator that represents atmospheric attenuation and dispersion and acts on p , and m represents the type of geometric spreading ($m = 1, 1/2$, or 0 for spherical, cylindrical, or planar propagation respectively). The GBE simultaneously accounts for nonlinear and dissipative effects and is used in sonic boom propagation programs like PCBoom (Lonzaga *et al.*, 2022) and sBoom (Rallabhandi, 2011).

Sonic boom propagation through a real atmosphere cannot usually be simply expressed as one type of geometric spreading. While in theory sonic booms spread cylindrically in a homogeneous atmosphere, refraction through the atmosphere tends to lead to more complicated spreading, or even focusing. One of the first practical solutions to this problem came from Hayes *et al.* (1968). This approach used a computer program to calculate ray tubes, the area of which corresponded to the focusing or defocusing of acoustic energy. This was successful and the same type of approach is employed in modern software packages.

2.2.3 Focus Booms

Vehicle maneuvers can have a tremendous impact on the sonic boom signatures experienced on the ground. The most-relevant maneuvers for rockets are acceleration and vehicle pitching. Both of these maneuvers tend to produce focus booms, sometimes called “superbooms”, on the ground. A focus boom occurs when multiple rays arrive simultaneously at a single location. For accelerating flight, this happens because the Mach cone angle changes as the vehicle accelerates, which enables rays emitted later to propagate a shorter distance to the same location as a ray that was emitted earlier. When pitching over, a similar phenomenon occurs, but the change in ray direction is caused by the change in aircraft orientation. A schematic of an acceleration-induced focus boom is shown in Fig. 2.2. Further studies and reviews on sonic boom focusing can be found in Plotkin and Cantril (1976), Salamone *et al.* (2013), Maglieri *et al.* (2014), and Page *et al.* (2015).

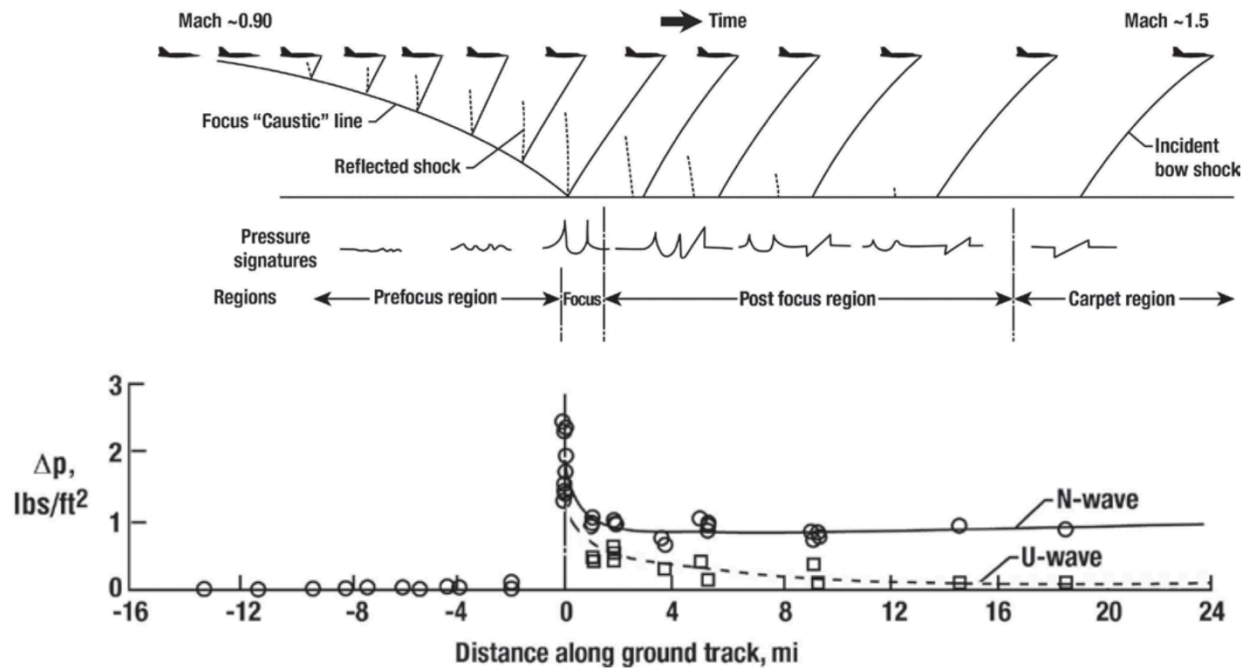


Figure 2.2 Illustration of sonic boom focusing. Adapted from Maglieri *et al.* (2014), which was in turn adapted from Maglieri *et al.* (1966, Not Publicly Available).

2.3 Launch Ascent

2.3.1 Apollo Saturn V Rocket

Measurements

Launch-ascent sonic boom measurements were made during the launch of Apollo 15 in 1971 and results were published by Hilton *et al.* (1972) (see also Hilton and Henderson (1974)). They used two ships located 87 and 970 km downrange of the launch site. At this point, it was unclear how to handle the exhaust plume effects, and thus it was not known whether predictions using existing theory were going to be accurate. To compensate for the uncertainty in the anticipated overpressure, three microphones were used on each ship and each microphone was connected to two different amplifiers for a total of six different measurement sensitivities.

The Apollo 15 measurements demonstrated that the launch-ascent sonic booms had a different shape than the traditional N-waves associated with other supersonic aircraft, and two example waveforms are shown in Fig. 2.3. The waveform measured at 87 km downrange has a clear front shock followed by a gradual rarefaction, with a secondary peak several seconds after the first. Hilton *et al.* (1972) attributed the secondary peak to possible focusing effects, concluding that the secondary peak was generated at an earlier time in the trajectory. The waveform at 970 km is more complicated, but still has a clear front shock. As for the negative peak at about 7.5 seconds in the 970 km waveform, Hilton *et al.* (1972) stated that the reason is not known.

Hilton *et al.* (1972) concluded that the exhaust plume controls the overall sonic boom magnitude and duration. They proposed that the large exhaust plume (which tends to expand as the vehicle reaches higher altitudes) produces a sonic boom with a greater overpressure than if only the rocket body were considered. The gradual waveform closure was attributed to the exhaust plume's indefinite length.

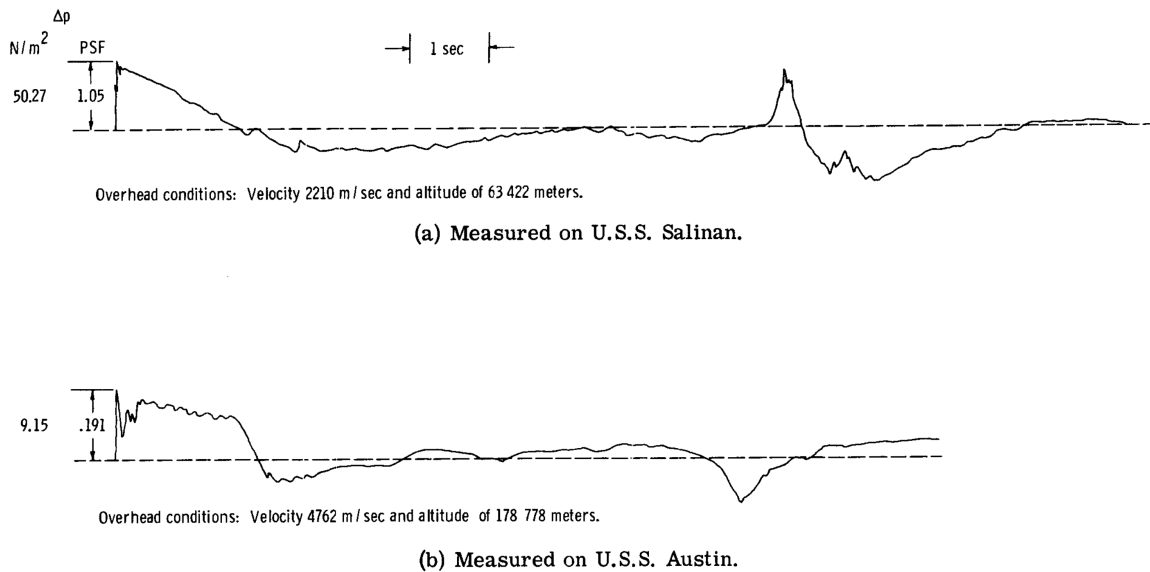


Figure 2.3 Apollo 15 launch-ascent sonic boom waveforms measured at (a) 87 km and (b) 970 km downrange of the launch site. Source: Hilton *et al.* (1972).

Similar measurements were made during the Apollo 16 mission, with results published by Henderson and Hilton (1974a) and Hilton and Henderson (1974). One of the goals of this measurement was to capture sonic booms in the focus region. To accomplish this, measurements were made aboard three ships located 69, 92, and 130 km downrange of the launch site. Figure 2.4 shows their measured waveforms. At the closest station (Fig. 2.4(a)), the waveform has two peaks, with the second appearing to be a separate signature superposed on the first. This is common for sonic booms in the focus region (Plotkin and Cantril, 1976; Salamone *et al.*, 2013; Page *et al.*, 2015). A similar waveform was measured at the middle station (Fig. 2.4(b)), but with the second peak occurring 19.6 seconds after the first, also similar to how focus boom signatures evolve as measured progressively farther from the focus. Lastly, the farthest station (Fig. 2.4(c)) shows no sign of a second peak, suggesting this recording was made relatively far from the focus.

Henderson and Hilton (1974a) also discuss the exhaust plume effects on the sonic boom signatures. They attributed the long signature durations to the indefinite length of the exhaust plume and that the exhaust plume increases the effective size of the rocket, leading to higher overpressures.

The final launch-ascent sonic boom measurement campaign using the Saturn V rocket was performed during the Apollo 17 mission and was reported by Henderson and Hilton (1974b). A primary objective was to further define the focus location. To do this, measurements were made

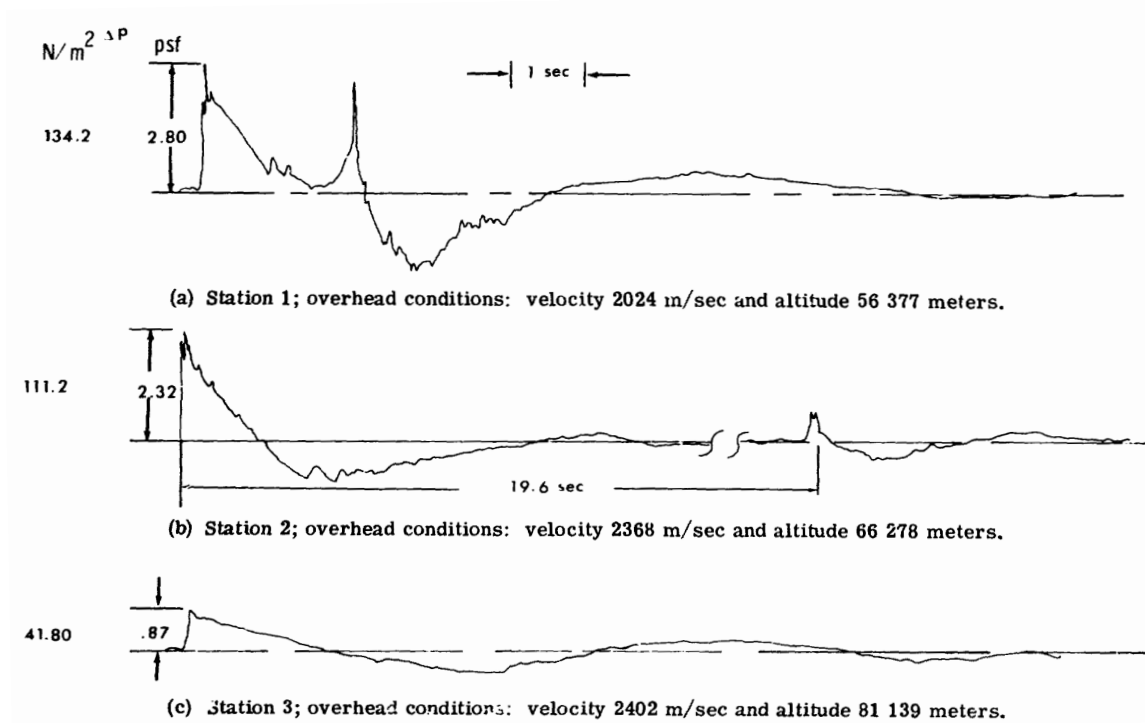


Figure 2.4 Apollo 16 launch-ascent sonic boom waveforms measured at (a) 69, (b) 92 and (c) 130 km downrange of the launch site. Source: Henderson and Hilton (1974a).

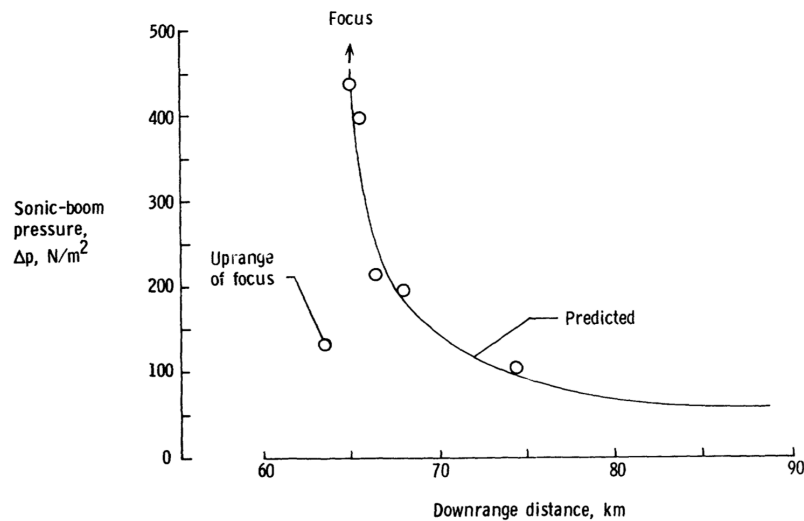


Figure 2.5 Apollo 17 launch-ascent sonic boom peak overpressures. Source: Henderson and Hilton (1974b). The predictions for peak overpressure come from (Holloway *et al.*, 1973).

aboard six ships located between 63–85 km downrange from the launch site, placing them near the predicted focus region. Their measured peak overpressures are shown in Fig. 2.5 along with the post-launch modeling by Holloway *et al.* (1973). The full waveforms are shown in Fig. 2.6, where some waveforms appear to show multiple arrivals indicative of being in the post-focus region. Unlike the Apollo 15 and 16 analyses, the Apollo 17 analysis provides estimates of conditions at which the booms were generated, rather than vehicle conditions from when the rocket passed overhead.

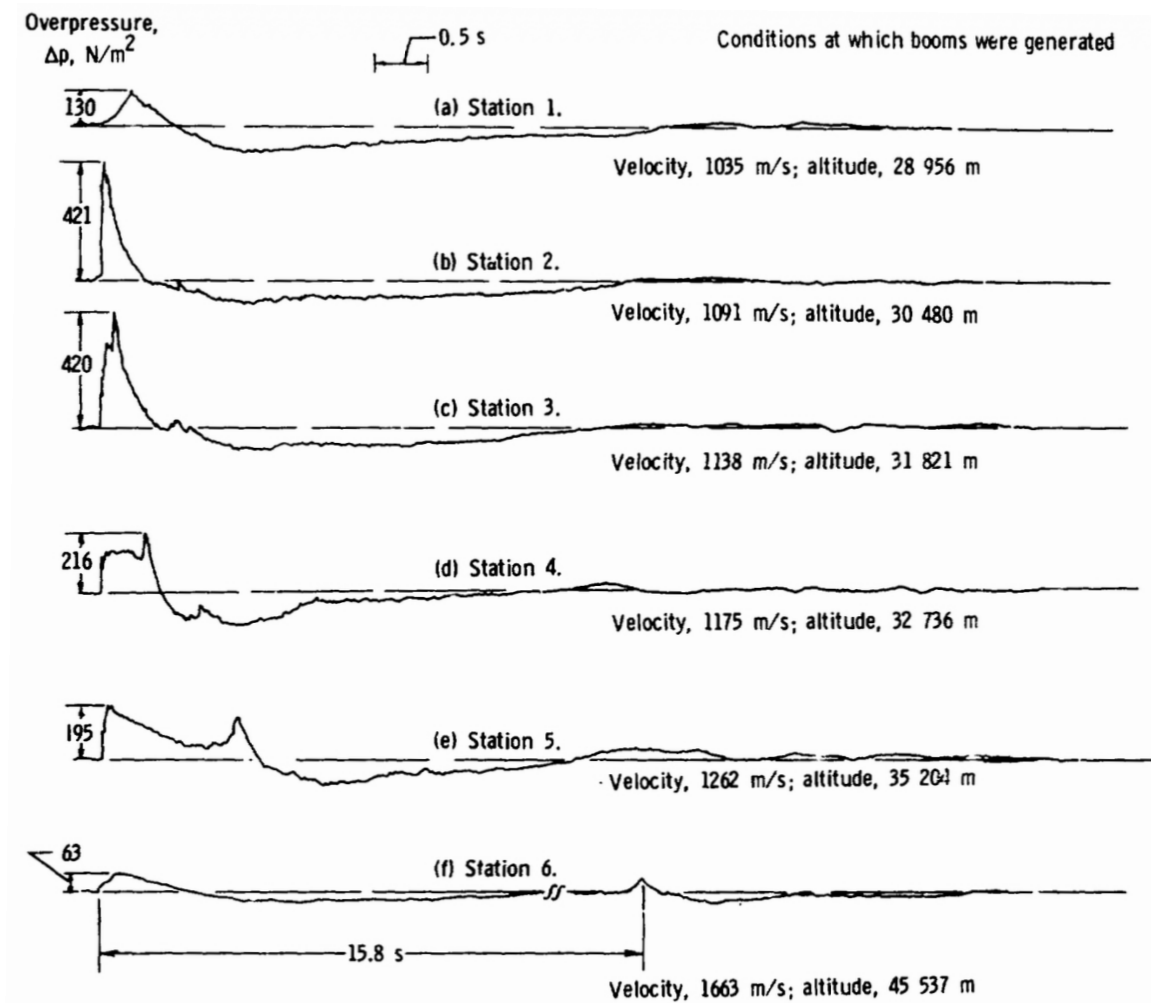


Figure 2.6 Apollo 17 launch-ascent sonic boom waveforms. Source: Henderson and Hilton (1974b).

Modeling

Wind-tunnel testing for the Saturn V rocket in ascent configuration was performed by Hicks *et al.* (1972b). Their goals included validating the NASA Ames sonic boom extrapolation program for hypersonic Mach numbers and to make predictions for the Apollo 16 launch-ascent sonic booms. They tested 0.00337 and 0.00168 scale models of the Saturn V in wind tunnels at Mach numbers between 3.01 and 7.91 with and without simulated exhaust plumes. Three different exhaust plume shapes were used to produce near-field pressure signatures for the Saturn V on ascent, and all three of them were conical.

Hicks *et al.* (1972b) also highlighted the fact that the near-field pressure signatures obtained during wind tunnel testing contained pressures that were too large to apply the typical sonic boom extrapolation techniques of the day. They discussed how extrapolation methods such as Thomas (1971) would produce inaccurate results and that a strong-shock extrapolation technique should be used, which they detail in an appendix. When the strong-shock technique was applied to pressure data measured for a sphere at a ballistic range, they found that the results were closer to measurements than when using the weak-shock techniques. They also stated that their strong-shock extrapolation method is likely only valid for the positive portion of the sonic boom signature.

Further wind-tunnel measurements were performed by Hicks and Mendoza (1973b). The primary goal of this study was to determine the appropriate length of a simulated exhaust plume required to accurately model the far-field sonic boom peak overpressure. They stated that the previous work by Hicks *et al.* (1972b) failed to accurately predict peak overpressures because their simulated exhaust plumes were too short and had no curvature. In the updated studies of Hicks and Mendoza (1973b), they used a simulated exhaust plume that was longer and curved, as shown in Fig. 2.7. Using this plume shape, they found that the predicted peak overpressure on the ground was accurate as long as the plume approached its asymptotic diameter before termination. In their study, they found that a plume length of 1.5 rocket body lengths was sufficient for peak overpressure predictions. They found that the primary effect of increasing the plume length beyond 1.5 rocket body lengths was to increase the signature duration. As their focus was on accurate peak-overpressure prediction, they did not determine the plume length required to accurately predict the total signature duration on the ground. They also stated that future experiments would involve high-pressure nitrogen gas to simulate the exhaust plume and determine the effectiveness of the solid plume envelopes used in this and previous studies (Hicks and Mendoza, 1973a).

Hicks and Mendoza (1973b) performed a study on strong-shock versus weak-shock extrapolation for the pressure signatures using the method of Hicks *et al.* (1972b). They measured the signature at 2.56 body lengths at Mach 4.01 and extrapolated the results to another measurement distance of 3.56 body lengths. The results are reproduced in Fig. 2.8. The strong-shock method better approximates the measured results, and they recommended using the strong-shock method presented by Hicks *et al.* (1972b) up to a distance where the overpressures are below half of the freestream pressure, after which they say it is appropriate to use the weak-shock technique detailed by Thomas (1971).

In preparation for the Space Shuttle program, Holloway *et al.* (1973) used Apollo data to develop models for sonic booms produced by blunt vehicles at high Mach numbers and altitudes. Although

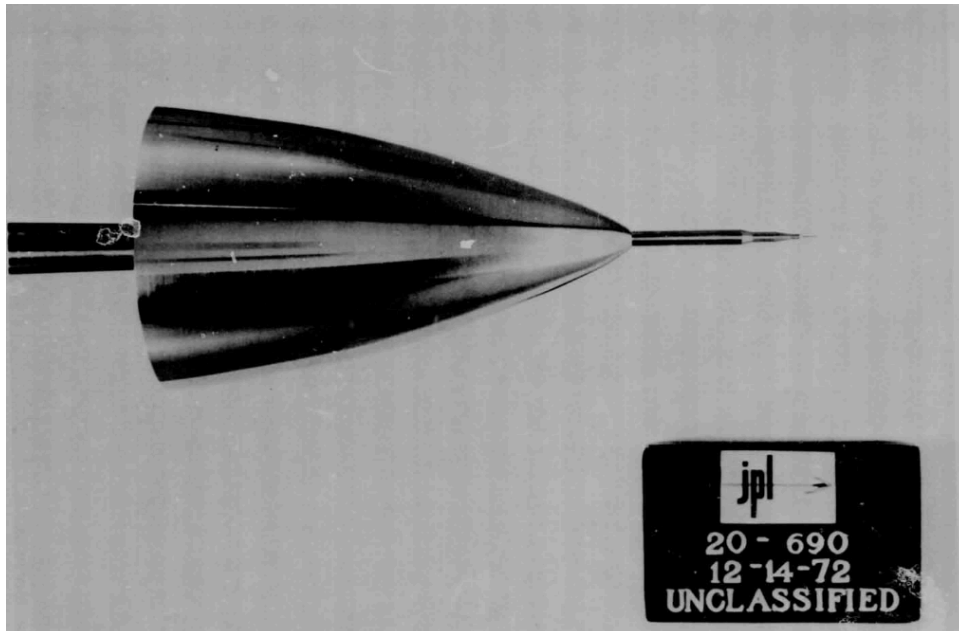


Figure 2.7 The 0.00053-scale model used by Hicks and Mendoza (1973b) to determine the required simulated plume length. Source: Hicks and Mendoza (1973b)

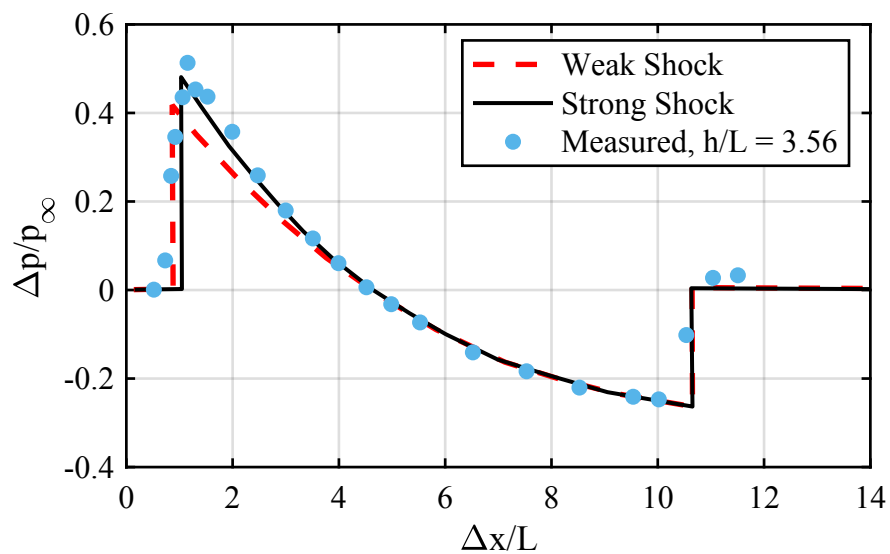


Figure 2.8 Comparing extrapolated signatures using the strong-shock and weak-shock techniques. Reproduced from Hicks and Mendoza (1973b) due to poor image quality.

the details related to the Space Shuttle are discussed further in Section 2.3.2, their work provided details regarding what they found to be an effective method for estimating the peak overpressure undertrack during Saturn V launches. Their method relied on using near-field signatures derived from wind tunnel measurements and then propagation to the far field using the waveform parameter method of Thomas (1972). For strong shocks, they propagated the signatures using the strong shock method in Hicks *et al.* (1972b) until the shocks were sufficiently weak to rely on the waveform parameter method. Using wind tunnel data with and without simulated exhaust plumes, they demonstrated that the exhaust plume results in a peak ground overpressure that is 4–10 times higher than if the exhaust plume had not been included in the simulation. They also discussed the modeling of such plumes in the wind tunnel, citing Hicks and Mendoza (1973a) as evidence that the exhaust plume can be accurately modeled as a solid body extending behind the model. Overall, they found that the peak overpressure undertrack near the focus region could be accurately predicted for the Saturn V launch vehicle, as illustrated previously in Fig. 2.5.

2.3.2 Space Shuttle

Measurements

All Space Shuttle sonic boom measurement campaigns were summarized by Maglieri *et al.* (2011). In total, three missions included launch-ascent sonic boom measurements. At present, most original reports for these three missions are not publicly available, therefore much of the information comes from the summaries contained in Maglieri *et al.* (2011) and a handful of other reports and theses.

A single measurement was made in the Atlantic Ocean near the focus region during the STS-5 launch (Garcia *et al.*, 1983b, Not Publicly Available) (see also Stanley (2005)). Launch occurred at 12:19 UTC on November 11, 1982. The measured sonic boom originated at about 34 km in altitude with the vehicle traveling at Mach 3.5. The measurement was made about 72 km east of the launch site (Garcia and Potter, 1983). The measured overpressure was 3.66 psf (1 psf = 47.88 Pascals) and the sonic boom duration was 5.70 seconds. The predicted overpressure using preliminary trajectory data was 3.10 psf (Garcia and Potter, 1983; Garcia *et al.*, 1983a).

For the STS-7 mission, seven measurements were made in the Atlantic Ocean, again targeting the anticipated focus region Stansbery *et al.* (1983, Not Publicly Available). The results are summarized in Table 2.1. The signatures classified as being at or near the focus had overpressures between 3.02–6.81 psf, with lower overpressures measured after the focus region. The signatures near the focus also tended to be shorter, being between 2.6–4.1 seconds long while the post-focus booms were between 7.4–8.2 seconds.

Fortunately, the report by Stansbery *et al.* (1983, Not Publicly Available) was recently made available to the author of this dissertation through a FOIA request, though it has yet to become publicly available online. Two measured waveforms are shown here, with Fig. 2.9 being the focus boom measured at Station 2 and Fig. 2.10 being the post-focus boom measured at Station 3. The post-focus signature appears remarkably similar in shape to the post-focus measurement in Fig. 2.4(a) for Apollo 16.

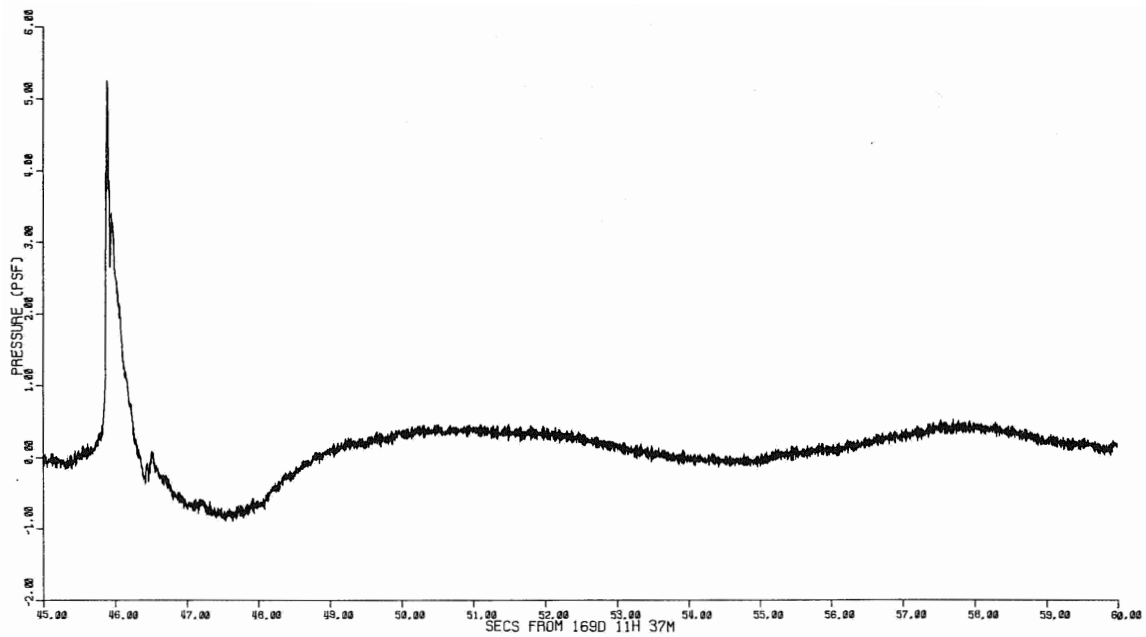


Figure 2.9 Measured focus boom at Station 2 during the STS-7 measurements. Reproduced from Stansbery *et al.* (1983)

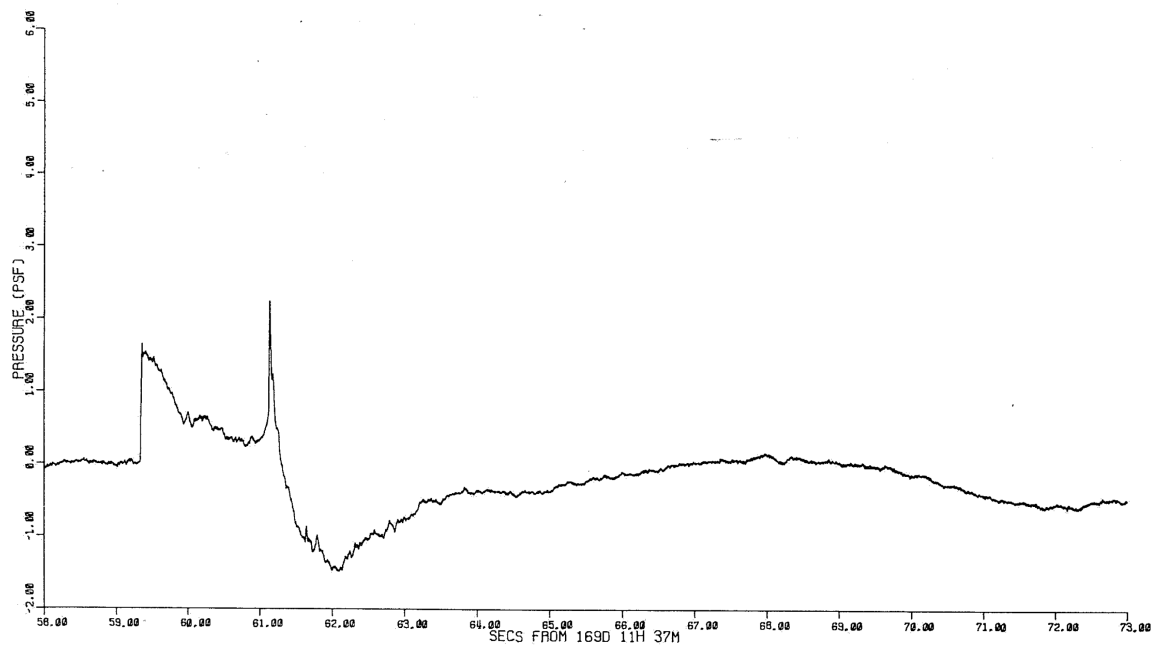


Figure 2.10 Measured post-focus boom at Station 3 during the STS-7 measurements. Reproduced from Stansbery *et al.* (1983)

Table 2.1 Measurement results for the STS-7 launch-ascent sonic boom. The sonic boom originated around 43–46 km in altitude at Mach numbers around 3.5–4.0.

Station #	Overpressure (psf)	Duration (s)	Classification
2	5.17	3.2	Focus
3	2.15	7.6	Post Focus
4	1.85	7.4	Post Focus
5	6.81	4.1	Focus
7	No Boom	No Boom	No Boom
8	3.02	2.6	Near Focus
9	0.66	8.2	Post Focus

Fifteen measurements were made during the STS-41D mission ascent (Stansbery and Stanley, 1984, Not Publicly Available). These results are summarized in Table 2.2. They only classified one of the measurements as being near the focus, and it had an overpressure of 3.62 psf. Overpressures ranged from 0.64–2.05 psf in the pre-focus region and 0.38–2.30 psf in the post-focus region. Near the focus region, the signature duration was 2.9 seconds. The signature duration ranged from 3.1–5.7 seconds in the pre-focus region and 1.7–5.4 seconds in the post-focus region.

Fortunately, additional information for the STS-41D launch-ascent sonic boom measurement campaign is provided in the thesis by Stansbery (1985). From here, we learn that the goal of the STS-41D measurements was not only to determine the focus region intensity, but also its lateral extent. Thus, the microphones were placed roughly along the predicted lateral extent of the focus. Importantly, Stansbery (1985) includes waveforms. These waveforms have been digitized and are reproduced in Fig. 2.11, along with a map that shows the locations for each measurement. As was the case for the Apollo launch-ascent sonic booms near the focus region, these waveforms are not N-waves and tend to have a large primary shock followed by a gradual rarefaction and return to ambient pressure. Several of the waveforms contain additional minor shocks, potentially indicating focusing effects. Interestingly, the reported peak overpressures in Stansbery (1985) and Maglieri *et al.* (2011) are not in perfect agreement. The overpressures reported by Stansbery (1985) are also shown in Table 2.2 immediately after those reported by Maglieri *et al.* (2011).

Using a high-altitude aircraft, O’Farrell and Rieckhoff (2011) directly visualized the shock waves forming around the Space Shuttle on ascent. A still image, taken at mission elapsed time (MET) 59.72 seconds, is shown in Fig. 2.12. As part of an effort to determine camera geometry relative to the shock structures, they also modeled the Mach cone refraction through the atmosphere. A plot showing where the Mach cone intersects the ground downrange is also shown in Fig. 2.12.

Modeling

Predictions for the Space Shuttle sonic booms during ascent were first reported by Holloway *et al.* (1973). They first validated their methods using Apollo 17 data (Henderson and Hilton, 1974b) and then applied the same techniques to the Space Shuttle. Their methods relied on wind tunnel

Table 2.2 Measurement results for the STS-41D launch-ascent sonic boom. The sonic boom originated around 46–52 km in altitude at Mach numbers around 3.5–4.0. Overpressures are those given by Maglieri *et al.* (2011) and Stansbery (1985) respectively. All other values are those reported by Maglieri *et al.* (2011).

Station #	Overpressure (psf)	Duration (s)	Classification
1	0.64 / 0.62	3.8	Pre Focus
2	1.36 / 1.42	4.0	Pre Focus
3	2.05 / 2.17	5.7	Pre Focus
U7	2.30 / 2.3	4.6	Post Focus
4	1.31 / 1.41	4.3	Pre Focus
U1	1.58 / 1.4	3.2	Pre Focus
U4	1.56 / 1.4	3.1	Pre Focus
5	2.23 / 2.23	3.5	Post Focus
6	1.14 / 0.83	5.3	Post Focus
7	0.38 / 0.37	4.7	Post Focus
U5	No Boom	No Boom	No Boom
U8	1.77 / 2.5	1.7	Post Focus
U3	3.62 / 3.2	2.9	Near Focus
U2	1.67 / 1.7	5.4	Post Focus
U9	No Boom	No Boom	No Boom

measurements and a combination of strong shock (Hicks *et al.*, 1972b) and weak shock extrapolation (Thomas, 1972) to determine the final signature at the ground. They also cautioned that the final vehicle control systems and trajectory were not yet available, but that their results were expected to be close to what would eventually be measured.

Holloway *et al.* (1973) calculated that, for a launch from Florida, the closest sonic boom would occur about 74 km offshore and that the footprint was expected to extend out to more than 92 km on either side of the ground track. They estimated that the sonic boom focal zone would be less than 3.7 km in length and extend out to about 83 km on either side of the ground track, narrowing with distance from the ground track. The peak overpressure was expected to rapidly decay with distance downrange of the focus. They also demonstrated that the focal zone dimensions were expected to vary with launch location, with the focal zone generated during launches from California expected to be smaller. They noted the importance of weather data for determining the final expected footprint for any given launch. The authors also briefly stated that operational constraints may be needed to avoid having the focal zone arrive on land in populated areas.

Glatt *et al.* (1975a) attempted to remove or minimize the Space Shuttle focus boom on ascent. This was a portion of a larger project to predict sonic booms using wind tunnel data. Coupling their wind tunnel data with trajectory information and a propagation program based on Thomas (1971) enabled optimization based on the ground-level sonic boom signatures. They found that the focus boom could not be eliminated, with a key contributor being the curved trajectory as the vehicle

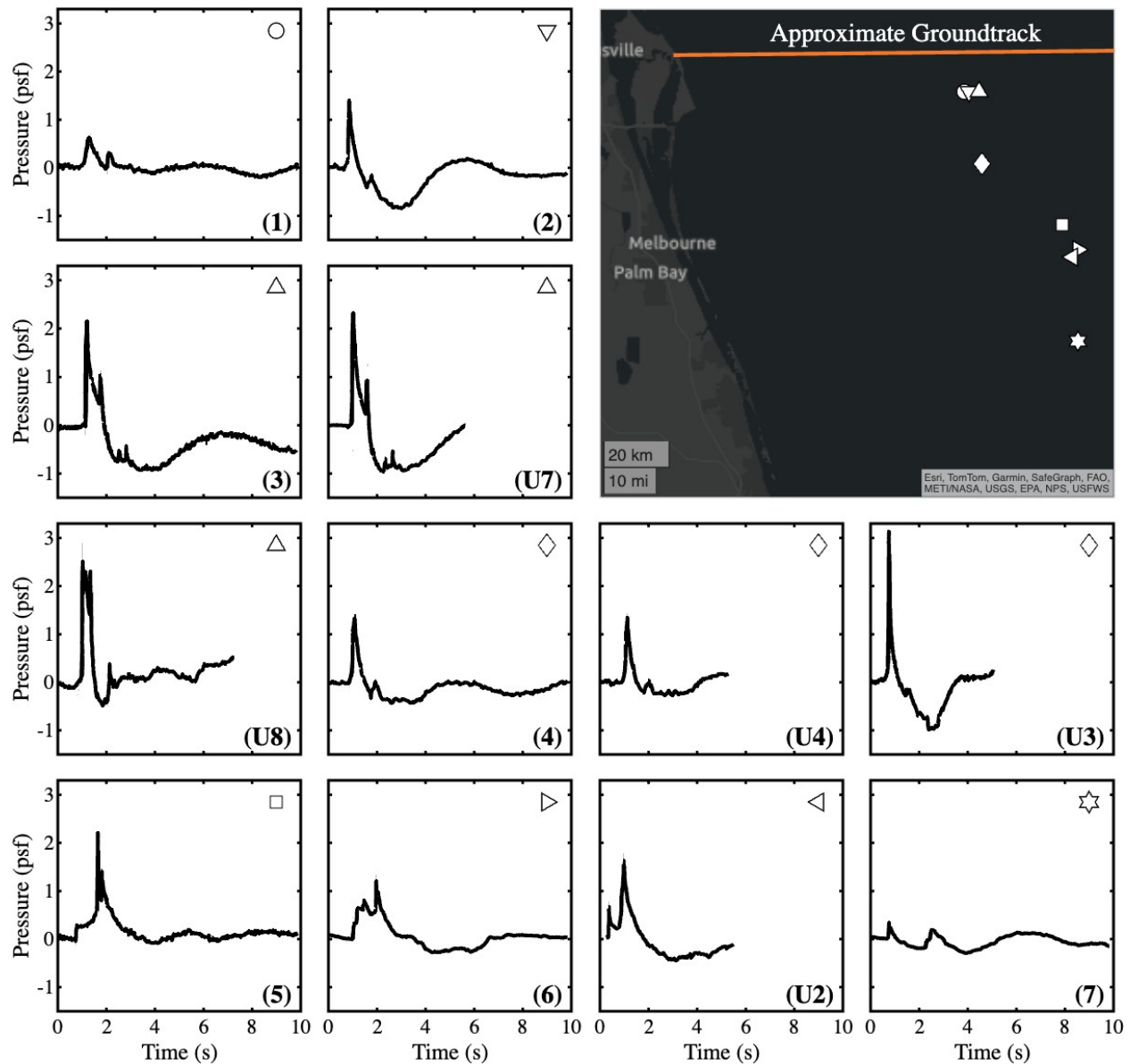


Figure 2.11 Measured waveforms from the STS-41D launch-ascent sonic boom measurements, digitized from Stansbery (1985) and compiled into a single figure here. The markers corresponding to each measurement's location are shown in the top-right corner of each subplot. Measurements that were made within 1 km of each other are considered colocated. The station number corresponding to Table 2.2 for each is shown in the bottom-right corner of each subplot. A single waveform was omitted (Site "U1") to improve plot formatting. This waveform was colocated with the other waveforms indicated by diamonds and was nearly identical in shape to the two waveforms shown at that same location.

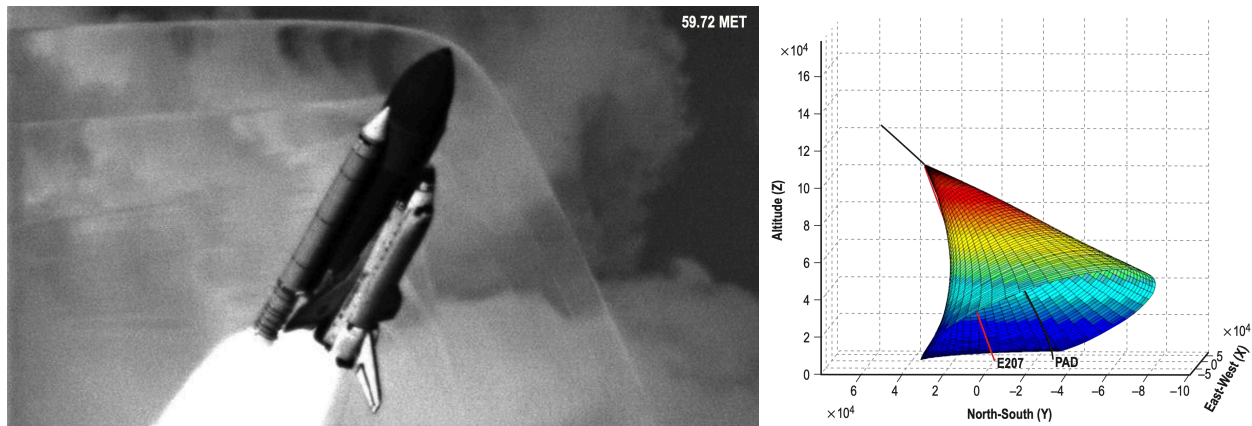


Figure 2.12 (Left) Direct images of shock waves around the Space Shuttle on ascent. (Right) Modeled shape of the Mach cone after refraction through the atmosphere. Both images are from O’Farrell and Rieckhoff (2011).

pitched over toward orbit. They determined that the best approach to minimize the focus boom was to generate the focus boom at a higher altitude because the extra propagation distance would reduce the ground overpressure. However, minimizing the focus boom overpressure negatively impacts the payload mass to orbit, with a 0.5% decrease in payload mass per 3 km of increased altitude where the focus boom is generated. Details regarding their wind tunnel database can be found in Glatt *et al.* (1975b).

The exhaust plume effects on the launch-ascent sonic boom for the Space Shuttle were studied by Mendoza (1975a). Although a previous study had performed similar wind tunnel measurements (Hicks and Mendoza, 1971a), those measurements had used an older design which employed a fully-reusable booster. The updated design, which appears very close to the final design, includes an expendable external fuel tank instead. Thus, the updated results by Mendoza (1975a) provided a needed improvement for Space Shuttle launch-ascent sonic boom predictions. He measured the near-field signatures both with and without simulated exhaust plumes at Mach numbers between 3.02–5.56 across multiple roll angles between 90–180°. Two example results are shown in Fig. 2.13 that demonstrate the importance of including the plume. On the left is a Space Shuttle on ascent (including the two solid rocket boosters, or SRBs for short). The near-field shock system is visible, with shocks originating at various locations along the vehicle. On the right is a similar model including a simulated exhaust plume made out of a solid body and designed to represent the mixing boundary. The strongest shock is clearly being generated by the plume’s interaction with the oncoming airflow. Because the shock due to the plume initially propagates at a steeper angle than the other shocks, the shocks produced by the rest of the vehicle are effectively “swallowed up” by the plume’s shock. Thus, Mendoza (1975a) demonstrates the importance of including the plume when determining the sonic boom signatures, a finding which agrees with conclusions from previous studies for the Apollo program as discussed in Section 2.3.1. Additional photographs and plots showing the near-field pressures at different test conditions are included in Mendoza (1975a).

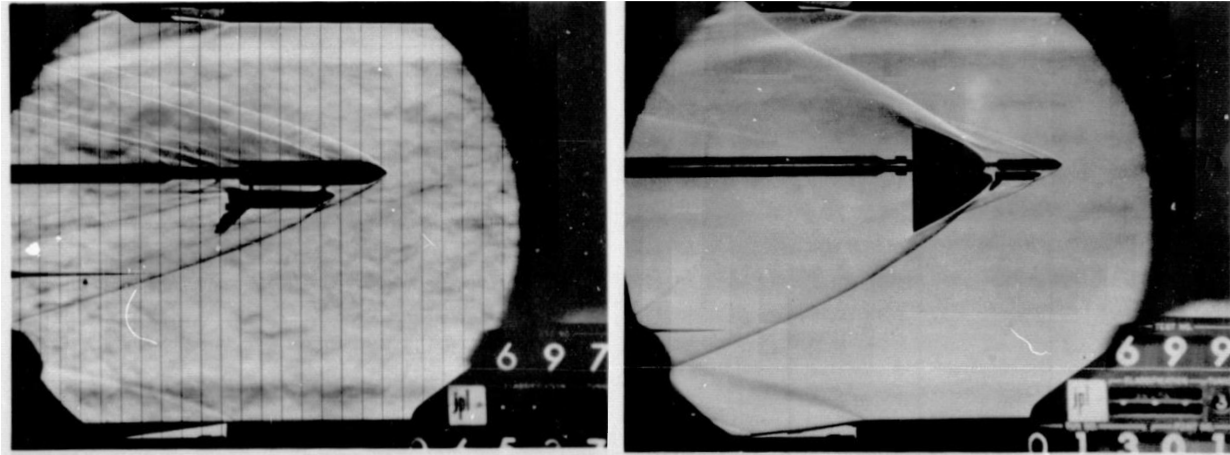


Figure 2.13 Wind tunnel comparison for a Space Shuttle model (left) without a plume model and (right) with a plume model. Both are shown at approximately Mach 4. Images are originally from Mendoza (1975a) and have been slightly cropped.

Cour-Palais (1977) published the conference proceedings from the 1976 Space Shuttle Environmental Assessment Workshop on Tropospheric Events. Confidence in the modeling comes from the work of Holloway *et al.* (1973), which had successfully modeled peak overpressures and arrival times for Apollo launch-ascent sonic booms. For the Space Shuttle ascent, the sonic boom was expected to land 74 km from the coast and have a width of over 186 km. The predicted focus was expected to be 3.7 km long and have a width of 166 km, narrowing toward the edges. They stated that it is possible that the width of the launch-ascent sonic boom footprint could be a limiting factor when choosing trajectories. Interestingly, Cour-Palais (1977) also mentions experience with sonic booms related to Skylab, but no references are given.

Similar to Mendoza (1975a), Ashby (1979) also performed wind-tunnel measurements on the Space Shuttle. Instead of fully modeling the vehicle on ascent, an equivalent body of revolution was used that represented the orbiter and external fuel tank. A solid-body extension representing the exhaust plume was also included. One difference was that Ashby (1979) used models that were very small, being only 0.000456 scale. The smaller characteristic length enabled measurements at 10.65 body lengths away from the wind tunnel model. Measured signatures at 10.65 body lengths were compared with predictions made using the codes of Marconi *et al.* (1976) and Marconi and Yaeger (1976). The results are shown in Fig. 2.14. To compensate for known limitations of the pitot and static probes in different portions of the flow field, Ashby (1979) produced the faired signature (black line) by favoring pitot probe data near the shock and static probe data farther from the shock. The final result agrees well with the computational predictions (+). Owing to this agreement throughout the results, Ashby (1979) concluded that computational methods are sufficient for estimating near-field sonic boom signatures and that limited wind tunnel measurements need only be performed to verify the results.

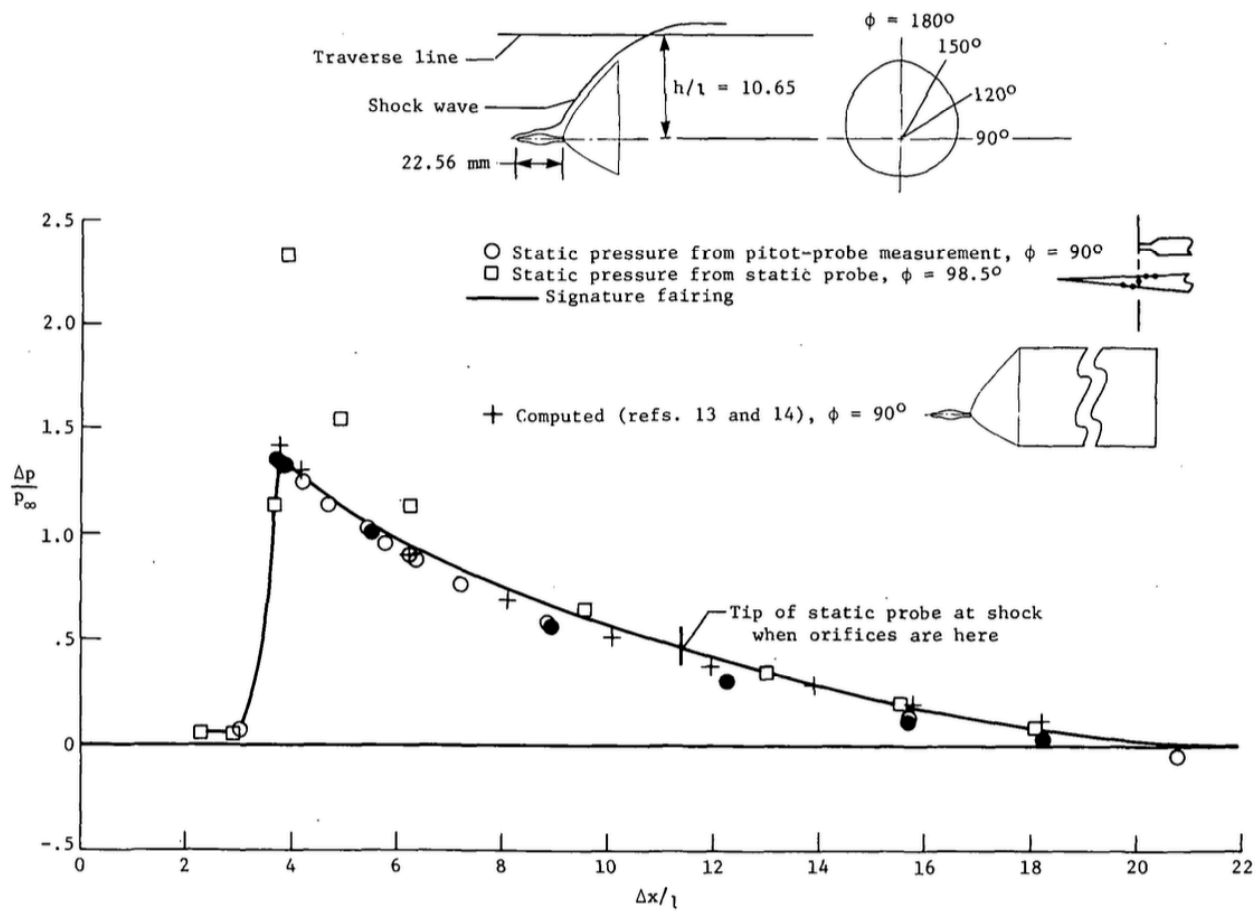


Figure 2.14 Measured and predicted waveforms at 10.65 body lengths away from the Space Shuttle. Figure reproduced from Ashby (1979).

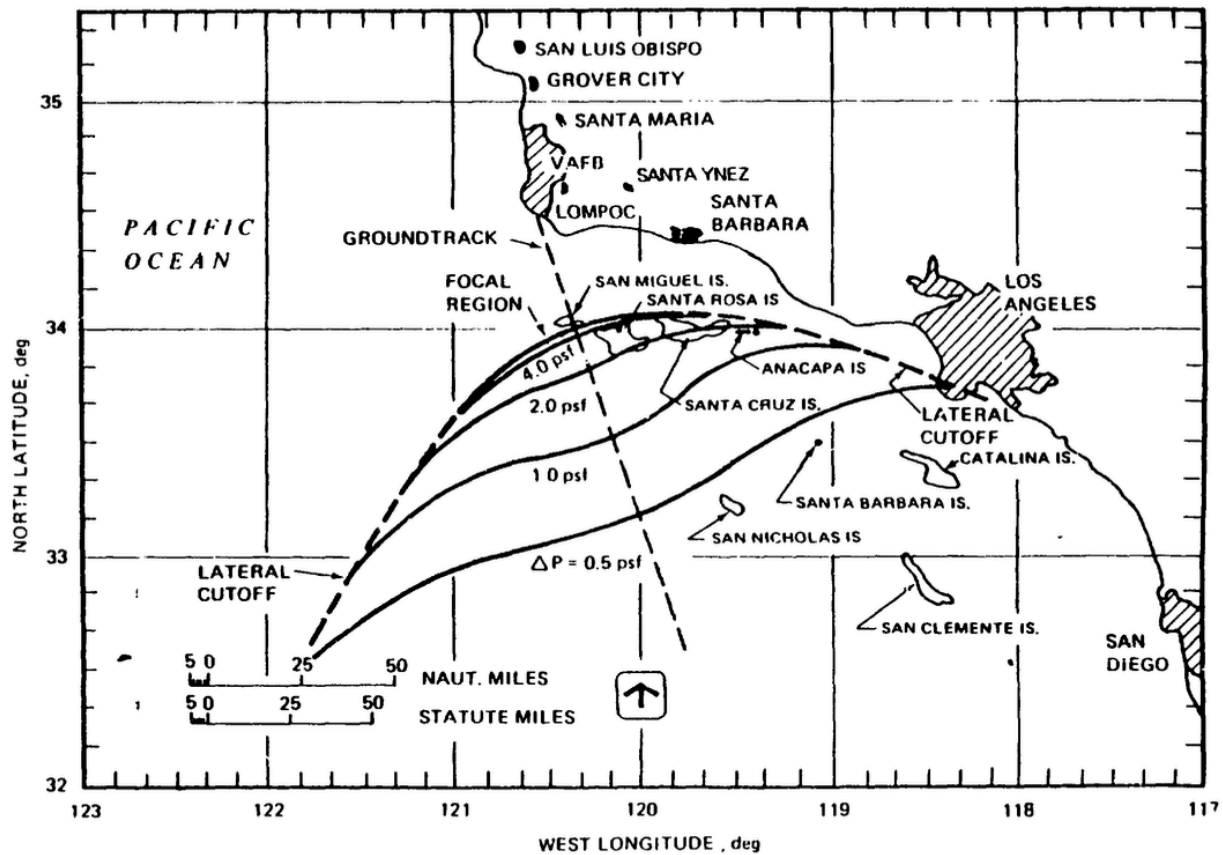


Figure 2.15 Predicted Space Shuttle launch-ascent sonic boom footprint when launching from VAFB. Figure reproduced from Wooten and Potter (1983).

Originally, the Space Shuttle had been planned to launch from both Florida and California, with the California launches originating from Vandenberg Air Force Base (VAFB). One of the concerns for VAFB launches was that the focus boom on ascent was predicted to land on the Channel Islands for certain trajectories, a potential concern for the local biology (Wooten and Potter, 1983). Although the Space Shuttle never launched from VAFB, precluding any actual measurements from this location, Fig. 2.15 shows a map of the predicted footprint from a launch at 150° azimuth. They also show the results of a parametric study by Haber (1981, Not Publicly Available) that describes the confidence limits for the focal region and the footprint to land on several of the islands. Overall, the 150° azimuth had substantially higher likelihoods of sonic booms landing on the islands when compared with trajectory azimuths of 180° and 193° .

Sonic booms from the Space Shuttle during ascent are briefly mentioned in the environmental impact statements for the Galileo and Ulysses missions (NASA, 1988, 1989). The ascent focus

boom was expected to occur 74 km off shore, in agreement with other sources, and have a peak overpressure of 3.66 psf.

2.3.3 Other Vehicles

Measurements have been made for several different rockets during ascent. These are summarized, with references, in Table 2.3. Further information for some vehicles are also given in this section.

Table 2.3 Historical launch-ascent sonic boom measurements. Apollo and Space Shuttle measurements are discussed above and not included in this table. If multiple shocks were recorded, only the highest overpressure is shown here. Sources with an asterisk next to them indicate that the source cites another document for their values but that document does not appear to be publicly available at this time.

Year	Vehicle	Launch Site	Measurement Site	Overpressure (psf)	Sources
1991	Titan IV	SLC-4E	SMI (San Miguel Island)	1.34, 1.89	Stewart (1993); Francine and Stewart (1995); Downing and Plotkin (1996)
1991	Titan IV	SLC-4E	Pt. Bennett (SMI)	1.8	NMFS and NOAA (2013)*
1996	Titan IV	SLC-4E	Crook Pt. (SMI)	8.92	NMFS and NOAA (2013)*
1999	Athena II	SLC-6	Adam's Cove (SMI)	1.0	NMFS and NOAA (2013)*
1999	Athena II	SLC-6	Pt. Bennett (SMI)	0.95	NMFS and NOAA (2013)*
2000	Delta II	SLC-2W	Pt. Bennett (SMI)	0.4	NMFS and NOAA (2013)*
2001	Atlas II	SLC-3E	Cardwell Pt. (SMI)	0.75	NMFS and NOAA (2013)*
2002	Delta II	SLC-2W	Pt. Bennett (SMI)	0.64	NMFS and NOAA (2013)*
2003	Atlas II	SLC-3E	Pt. Bennett (SMI)	0.88	NMFS and NOAA (2013)*
2004	Delta II	SLC-2W	Adam's Cove (SMI)	1.34	NMFS and NOAA (2013)*
2006	Delta II	SLC-2W	SMI	0.0	USAF (2018)
2008	Atlas V	SLC-3E	Cardwell Pt. (SMI)	1.24	NMFS and NOAA (2013)*, Ortt (2015)*, USAF (2018)
2009	Delta II	SLC-2W	West of Judith Rock (SMI)	0.76	NMFS and NOAA (2013)*
2011	Atlas V	SLC-3E	Cuyler Harbor (SMI)	1.01	NMFS and NOAA (2013)*
2011	Delta II	SLC-2W	SMI	0.67	USAF (2018)
2012	Atlas V	SLC-3E	Cardwell Pt. (SMI)	2.10	NMFS and NOAA (2013)*
2013	Atlas V	SLC-3E	SMI	0.0	USAF (2018)
2014	Atlas V	SLC-3E	Cardwell Pt. (SMI)	0.74	NOAA (2019)*, USAF (2018)
2014	Atlas V	SLC-3E	Active Pt./Pt. Bennett (SMI)	1.18	Ortt (2015)*, NOAA (2019)*, USAF (2018)
2015	Atlas V	SLC-3E	East Adam's Cove (SMI)	1.96	NOAA (2019)*, USAF (2018)
2017	Atlas V	SLC-3E	Cuyler Harbor (SMI)	2.2	NOAA (2019)*, USAF (2018)
2022	Falcon 9	SLC-4E	SMI	1.58	USSF (2022)
2022	Delta IV Heavy	SLC-6	SMI	0.2	USSF (2022)
2023	Falcon 9	SLC-4E	SMI	1.09	USSF (2023)

Titan IV

Measurements of a Titan IV rocket launch-ascent sonic boom from VAFB were made in 1991 (Stewart, 1993; Francine and Stewart, 1995; Downing and Plotkin, 1996). Predictions were made with PCBoom 3 and measurements were made at two locations on San Miguel Island south of the launch location. The sonic boom arrived 4 minutes and 38 seconds after the launch and most of its energy was below 500 Hz. The flat-weighted sound exposure level was 124 dB and the A-weighted sound exposure level was 78 dB. The sonic boom signature contained multiple positive peaks and was neither an N-wave nor a U-wave. Francine and Stewart (1995) attributed this to the measurements being downrange of the actual focus location. The two peak overpressures measured were 1.34 and 1.89 psf. While Stewart (1993) stated that the measured peak flat-weighted sound pressure level on San Miguel Island was 129.5 dB, the anticipated peak pressure level in the focal region was ≥ 150 dB. It is suggested by Francine and Stewart (1995) that more measurements need to be made to validate models in the focus region, including accurate knowledge of focus-boom frequency content.

Titan IV launch-ascent sonic booms are also discussed in USAF (1990). It was expected that the Titan IV sonic boom would be less intense than the Space Shuttle because the Titan IV rocket and exhaust plume were expected to be smaller than the Space Shuttle. The potential for focus booms of 10 psf over the Channel Islands was discussed. This report was also cited by NASA (1994) to explain that sonic booms were not expected to pose a problem for the Mars Pathfinder launch.

Atlas V

The Atlas V rocket was studied as part of the Evolved Expendable Launch Vehicle Program, with environmental assessments published by FAA (1998) and FAA (2000). Originally, the Atlas V was referred to as “Concept A”. For launches from Florida, the sonic booms were expected to occur only over the Atlantic Ocean, with a peak overpressure of 6–8 psf. The same peak overpressure would be expected for launches from VAFB, but the edges of the carpet could impact the mainland for the more-easterly trajectories. The Channel Islands were also expected to experience sonic booms from the launches.

Brief mention is made in the Mars 2020 final environmental assessment (NASA, 2014) that the predicted sonic boom footprint would be about 48 km offshore at its closest point.

Ortt (2015) provided two measured waveforms for the Atlas V, which have been digitized here and are reproduced in Fig. 2.16. The waveforms are similar to those discussed previously for the Saturn V and Space Shuttle.

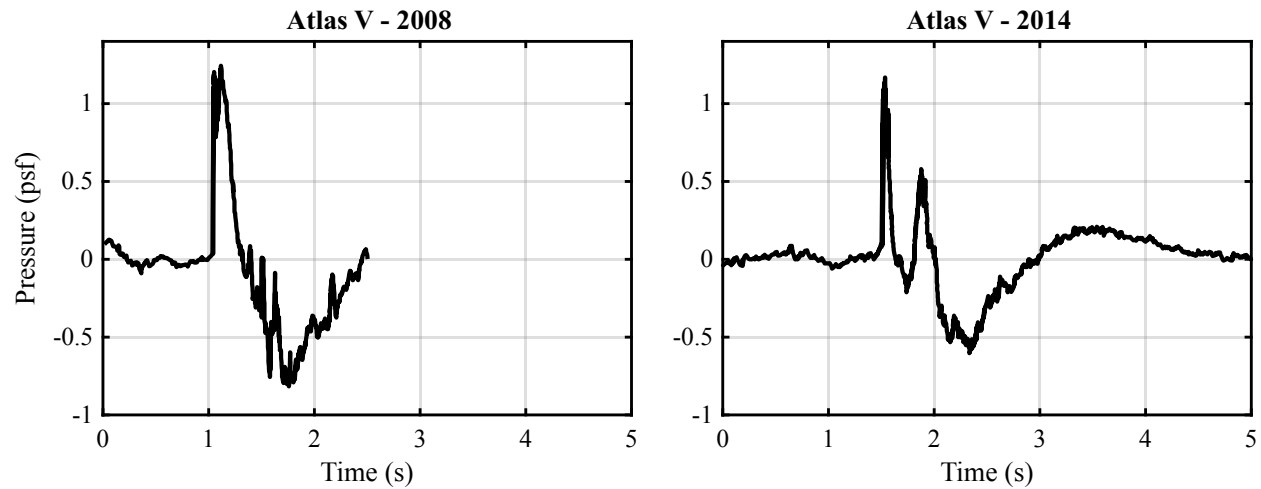


Figure 2.16 Measured Atlas-V launch-ascent sonic booms on San Miguel Island. Waveforms digitized from Ortt (2015). The 2008 waveform is attributed to “SRS Technologies 2008”, but details about that reference are not given by Ortt (2015).

Delta IV

The Delta IV rocket was also studied as part of the Evolved Expendable Launch Vehicle Program, with environmental assessments published by FAA (1998) and FAA (2000). Originally, the Delta IV was referred to as “Concept B”. For launches from Florida, the sonic booms were expected to occur only over the Atlantic Ocean, with a peak overpressure of 6–8 psf. The same peak overpressure would be expected for launches from VAFB, but the edges of the carpet could impact the mainland for the more-easterly trajectories. The Channel Islands were also expected to experience sonic booms from the launches.

Falcon 1

Launch-ascent sonic boom overpressures were calculated for trajectories out of VAFB and are recorded in a 2007 environmental assessment (Aerostar Environmental Services, 2007). Using PCBoom 3, they analyzed the effects of winds and trajectory on the peak sonic boom overpressure, and the results are shown in Table 2.4. Three different December wind profiles were used, representing the mean and ± 3 standard deviations. This table illustrates the dependence of overpressure on wind and trajectory.

A comparison was also made with an Atlas IAS rocket that launched in 2001. The trajectory and nominal winds near the launch date were input into PCBoom 3 and the highest overpressure was found to be 4.0 psf. Comparisons were not made with different headings or varying the winds for the Atlas IAS launch. Aerostar Environmental Services (2007) provide contour maps for all of these simulations.

Table 2.4 Predicted peak overpressure values for a Falcon 1 launch from VAFB with three different headings and three December wind profiles (mean and $\pm 3\sigma$, or standard deviation, winds). Overpressures are given in psf. Data from Appendix G of (Aerostar Environmental Services, 2007).

	160°	175°	190°
-3 σ	1.67	8.92	1.87
Mean	2.65	2.02	7.05
+3 σ	2.48	10.14	3.95

X-15

Motivated by the upcoming Space Shuttle program, Green and Putnam (1974) investigated the sonic booms from the X-15 rocket-powered aircraft. They wanted to measure sonic booms from a slender body flying faster than Mach 3 so that they could ensure accurate predictions for future Space Shuttle reentry sonic booms below 30 km. Their analysis is included in the launch-ascent sonic booms portion of this review because their results are insightful for understanding exhaust plume effects. Measurements were made in Goldstone Dry Lake and Cuddeback Dry Lake near Edwards Air Force Base, California. The X-15 was released from its B-52 carrier aircraft at 13.7 km, burned its engine for 97 seconds, and shut down at Mach 4.8 at an altitude of 21.7 km. While the original plan called for the vehicle to directly overfly the measurement locations, it actually passed 2.7 km away from Goldstone Dry Lake and 12.6 km away from Cuddeback Dry Lake. The Goldstone Dry Lake boom (Mach 4.8) was predicted to have a peak overpressure of 31.4 Pa and was measured at 34.4 Pa. The Cuddeback Dry Lake boom (Mach 3.5) was predicted to have a peak overpressure of 28.5 Pa and was measured at 25.0 Pa. Although the measurements agree to within 12% of the predictions, it is worth noting that Green and Putnam (1974) stated that their measurement hardware is estimated to have an uncertainty of $\pm 15\%$.

The data from Green and Putnam (1974) were used by Maglieri *et al.* (2014) to demonstrate the influence of the exhaust plume and speed brakes on the tail shock in the final signature. Figure 2.17 shows two conditions. On the left are the waveforms measured at Cuddeback Dry Lake, which were produced while the engine was not firing and the speed brakes were not deployed. The signatures tend to have a clear closure at the tail shock. On the right are the waveforms measured at Goldstone Dry Lake, which were produced while the engine was firing at 50% thrust and the speed brakes were deployed. While the front shock is well defined, the waveform closes with a more gradual recovery to ambient pressure. Maglieri *et al.* (2014) concluded that the plume and wake produced by the speed brakes increases the effective vehicle length and cause the more gradual signature closure. They suggest that future studies could include exhaust plume shaping to reduce the effects from the tail shock on both people and structures.

An additional part of the analysis by Green and Putnam (1974) was a scaled comparison to measured SR-71 data flying at a similar altitude at Mach 3.0 (Maglieri *et al.*, 1972). They provided equations and a discussion of the scaling methodology, including contributions of volume and lift

on the final signature, in their report. Overall, they stated that the agreement between the SR-71 and scaled X-15 data was good.

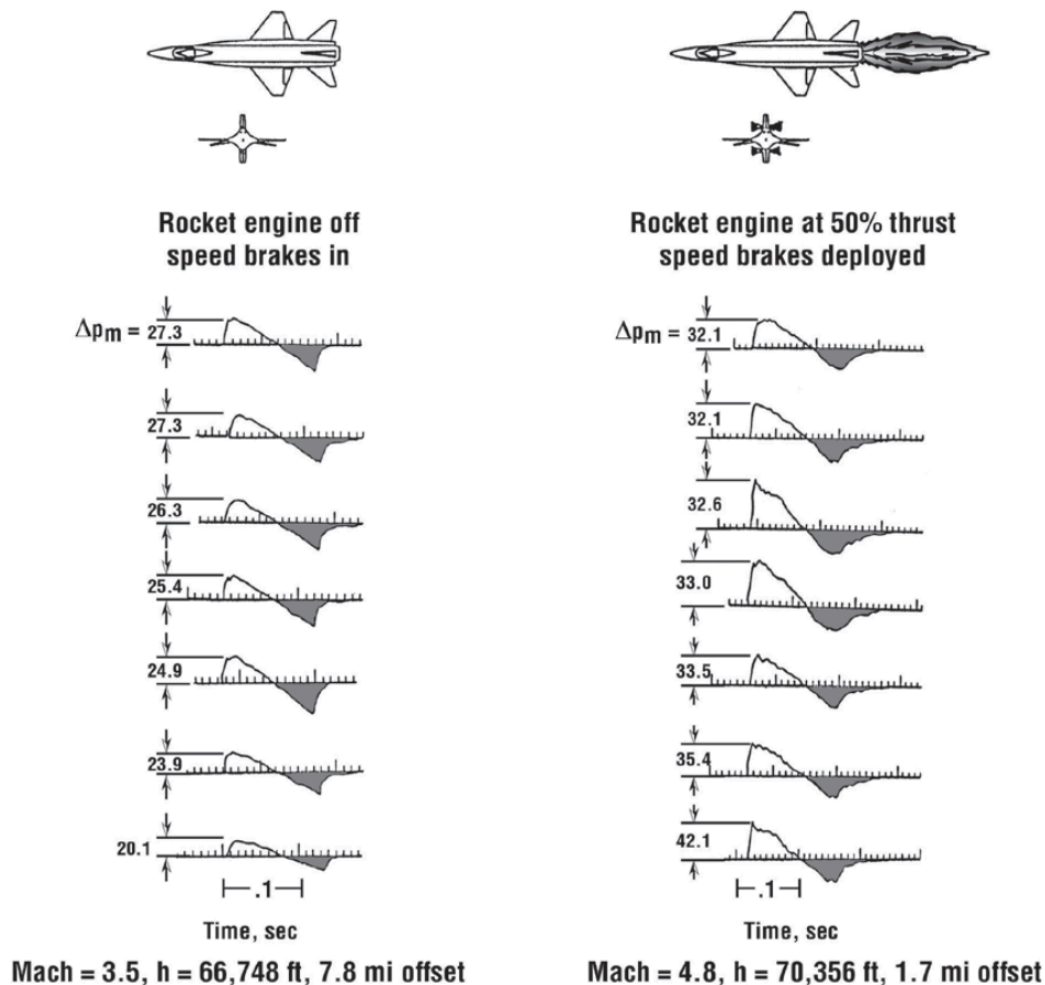


Figure 2.17 Sonic boom waveforms produced by the X-15 rocket-powered aircraft, both with and without the engine and speed brakes being used. Figure reproduced from Maglieri *et al.* (2014), which was adapted from Green and Putnam (1974).

Apollo 12 and 13 (Saturn V)

During the Apollo 12 and 13 launches, measurements were made in Bermuda and reported on by Cotten and Donn (1971) and Cotten *et al.* (1971). These measurements were not discussed above alongside the other Saturn V results because they are so far away from the launch location and represent a different regime of flight. These sonic booms were generated while the vehicle was 188 km above the ground. By comparing arrival times and coherence across their different sensors they demonstrate that the signatures most likely come from the Saturn V passing nearly

overhead. Additionally, they performed theoretical work to validate their claims that the very large underexpanded exhaust plume at those altitudes could produce a pressure signature that would be detectable on the ground.

2.3.4 On Simulating Exhaust Plumes Using Solid Bodies

It may be initially surprising to learn that the exhaust plume produces such a strong shock and greatly impacts the final sonic boom signatures on the ground. The work of Hicks and Mendoza (1973a) demonstrates that this is true. Because this is central to the formation of rocket launch-ascent sonic booms, their results have been reproduced and reorganized here for easier visualization.

First, Fig. 2.18 demonstrates the importance of considering the exhaust plume when performing sonic boom studies for rockets during launch. As the rocket ascends, the ambient air pressure decreases and the exhaust flow becomes underexpanded, meaning (perhaps confusingly) that the plume expands after exiting the nozzle. The first row of Fig. 2.18 shows a simplified rocket body consisting of a cone and a cylinder in a wind tunnel at freestream Mach numbers of 2.94 and 3.92. This simplified rocket body was able to eject nitrogen gas to create an underexpanded exhaust plume (shown in the second row of Fig. 2.18). Pressure measurements were made along a line parallel to the rocket to capture the shock patterns both with and without the nitrogen plume turned on. The plots in the third row of Fig. 2.18 show the pressure results. When the nitrogen plume is included, the shock amplitudes are substantially greater because a strong shock forms just ahead of the exhaust plume, demonstrating the importance of including the exhaust plume in sonic boom studies for rockets.

In many cases, it is simpler to represent the exhaust plume as a solid body behind the rocket model. To do this, the solid-body plume must be sized appropriately. Hicks and Mendoza (1973a) set out to determine whether the solid-body plume model should follow the dimensions for the plume inner shock or the mixing boundary. Their experiments at freestream Mach numbers of 2.94 and 3.92 are shown in Figs. 2.19 and 2.20 respectively. The measured pressure signatures indicate that the solid-body model that follows the mixing boundary better matches the pressure signatures produced with the actual nitrogen plume. They also noted that the mixing boundary pressure curves show a distinct change in derivative some distance behind the plume-induced shock. This was attributed to the expansion fan generated at the simulated exhaust plume termination and they stated that this would not happen if the solid-body model were longer. They recommended using longer plume models at higher Mach numbers to prevent this effect from decreasing the bow shock overpressure. Hicks and Mendoza (1973a) also stated that these results focus on only the positive portion of the pressure signature and that obtaining the full signature would require modeling the full flow field produced by the exhaust.

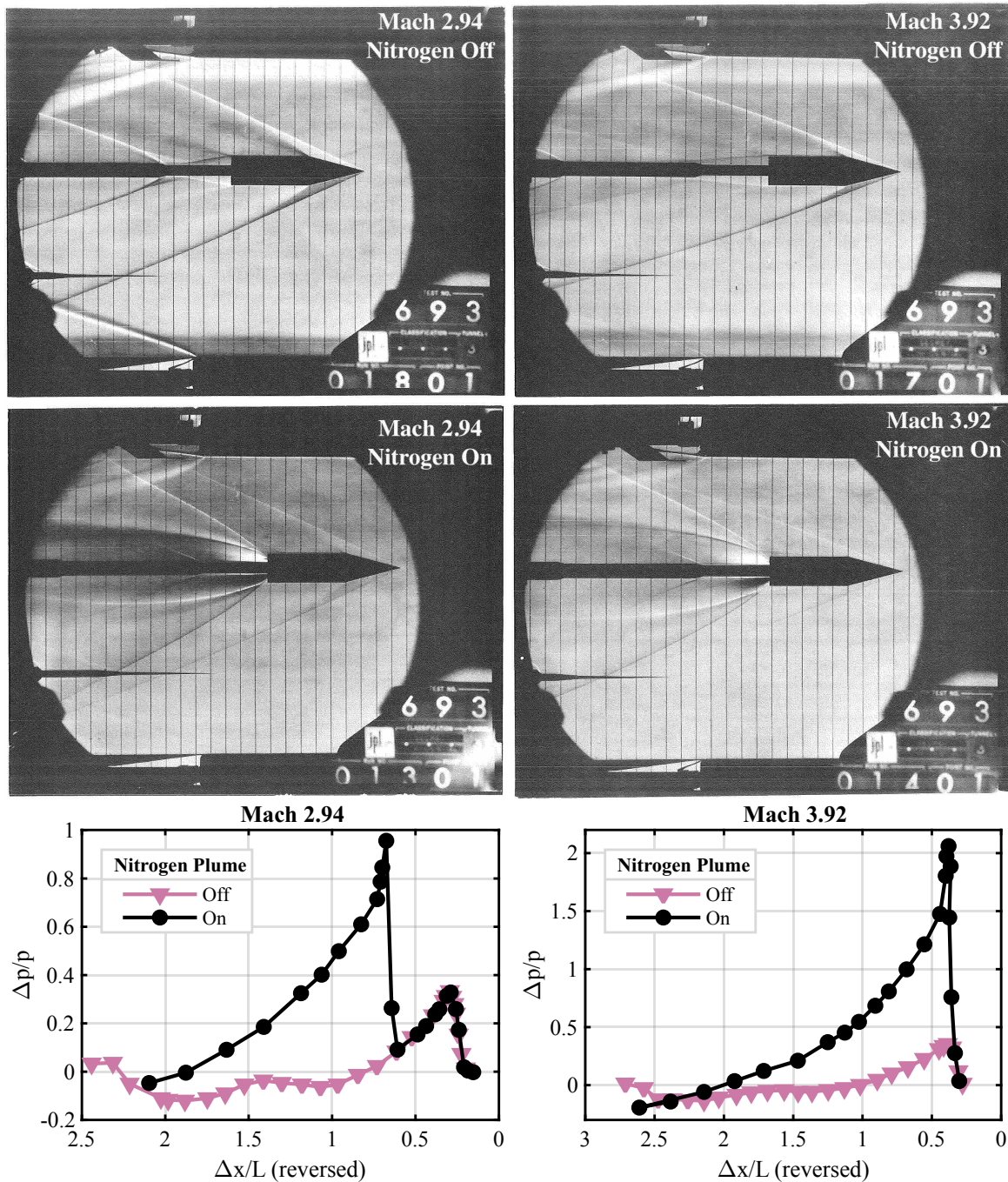


Figure 2.18 Wind tunnel measurements of a rocket with and without a nitrogen plume turned on, run at freestream Mach numbers of 2.94 and 3.92. The plots on the third row show the pressure measurements made at both freestream Mach numbers and have been digitized from Hicks and Mendoza (1973a). The data have been aligned here according to their front shocks. Text in the upper right corners of the photographs has been added here for clarity.

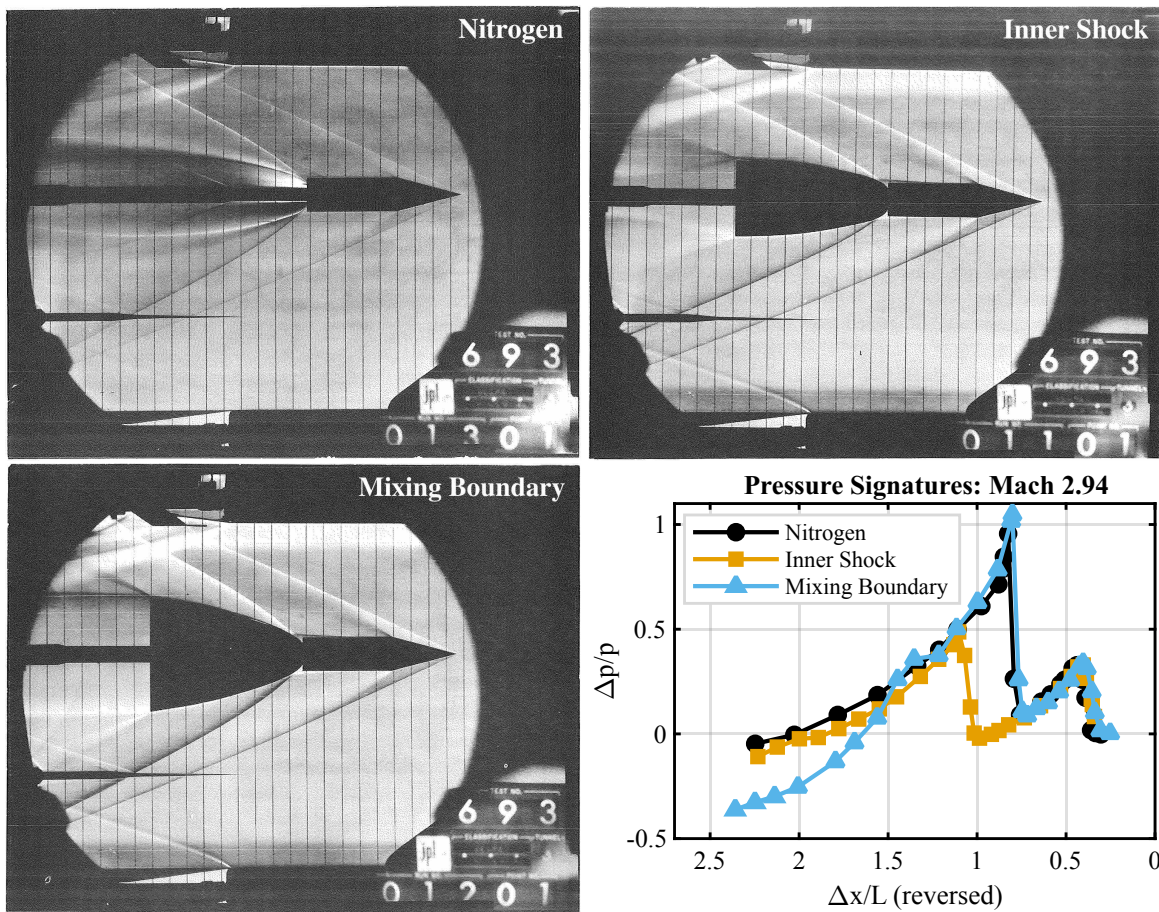


Figure 2.19 Comparison of two solid bodies representing the inner shock and mixing boundary regions of the exhaust plume to determine which produces a shock wave pattern most similar to the actual nitrogen plume. This case was run at a freestream Mach number of 2.94. Images and data come from Hicks and Mendoza (1973a). Text in the upper right corners of the photographs has been added here for clarity.

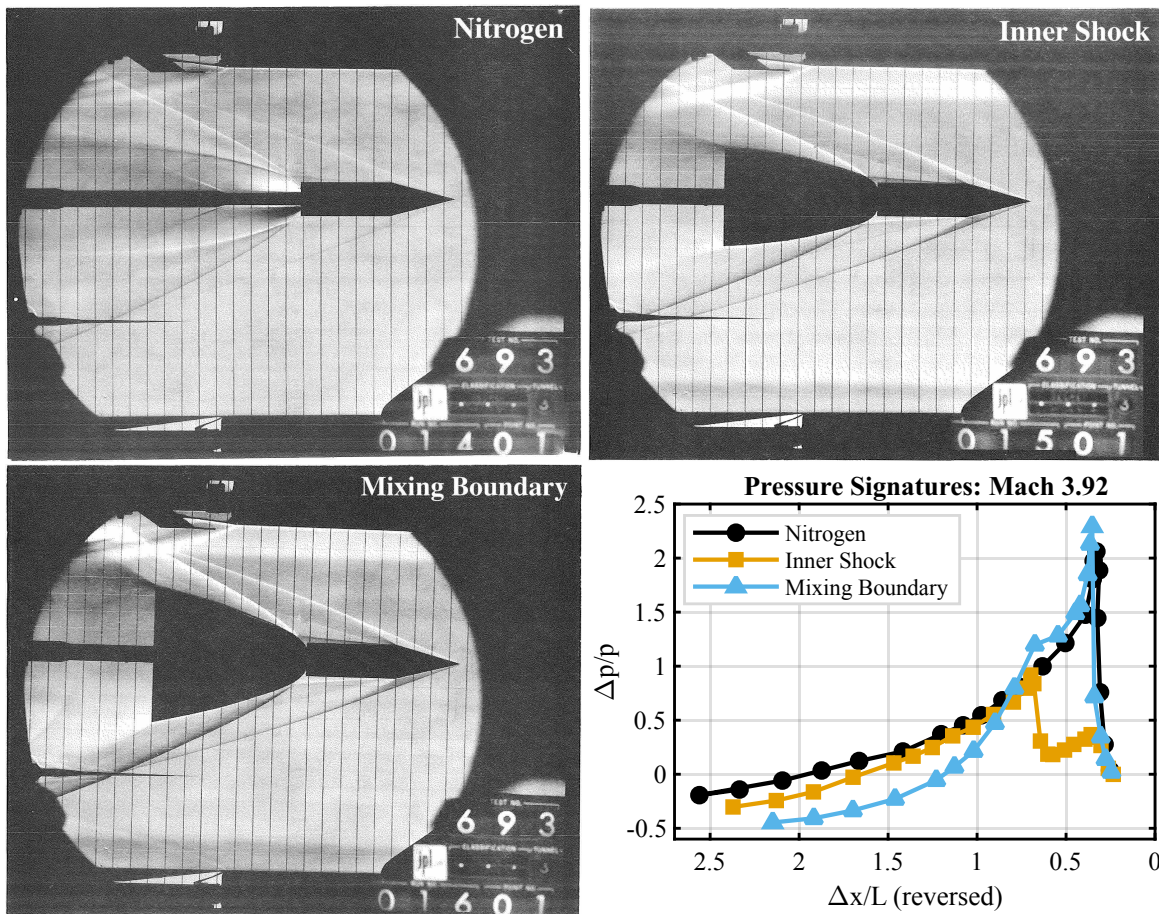


Figure 2.20 Comparison of two solid bodies representing the inner shock and mixing boundary regions of the exhaust plume to determine which produces a shock wave pattern most similar to the actual Nitrogen plume. This case was run at a freestream Mach number of 3.92. The nitrogen front shock location was adjusted in the plot to align with the location for the other lines in this plot. Images and data come from Hicks and Mendoza (1973a). Text in the upper right corners of the photographs has been added here for clarity.

2.4 Spacecraft Reentry

2.4.1 Apollo Capsule

Measurements

Capsule reentry measurements were made during the Apollo 15 mission reentry over the Pacific Ocean (Hilton *et al.*, 1972; Hilton and Henderson, 1974). Three ships were stationed in the ocean under the reentry track at 500, 55.6, and 12.9 km from the splashdown location. The sonic booms measured at each of these locations are shown in Fig. 2.21. The capsule reentry sonic booms are much shorter than the launch-ascent sonic booms, lasting a few tenths of a second, though they are still longer than most traditional aircraft sonic booms. Another difference between the capsule reentry and launch-ascent sonic booms is that the capsule reentry sonic booms tend to have a more-definitive signature termination.

Hilton *et al.* (1972) discussed the multiple-shock behavior observed in the measurements, noting that it was not expected based on wind tunnel measurements. Although they stated that reasonable precautions were made against placing the microphones near a reflecting surface, they could not rule out the possibility that reflections off nearby surfaces occurred. They also observed that there is a progression between the three measurements from a waveform with lots of small shocks superposed on the main signature to a few well-defined larger shocks that make the overall final signature shape more complicated. Although they did not mention it, the waveforms measured aboard the USS Kawishiwi and the USS Okinawa do have similar overall shapes while the waveform measured aboard the USS Genesee is different.

Measurements were also made during the capsule reentry of Apollo 16 (Henderson and Hilton, 1974a; Hilton and Henderson, 1974). Overall, the findings were similar to Apollo 15. Henderson and Hilton (1974a) concluded that the additional shocks in the waveform come from reflections, again noting that the extra shocks are not expected based on wind tunnel data.

Modeling

Driven by the need to validate sonic boom models for similar flight conditions as the upcoming Space Shuttle, Mendoza and Hicks (1971) made wind tunnel measurements of a 0.016-scale Apollo command module between Mach numbers of 1.50–10.02. These tests were all performed at an angle of attack of 25° while the roll angle was varied from 0–180°. Figure 2.22 shows a photograph of the command module in the wind tunnel with shocks clearly visible.

Hicks *et al.* (1972b) also discussed wind tunnel measurements made of the command module. Measurements were made at Mach 10.1 at an angle of attack of 25° for varying roll angles between 0–180°. They found that a secondary shock appearing behind the bow shock, but still in the positive-pressure phase of the signature, was not due to the sting as originally thought by Mendoza and Hicks (1971). Rather, ballistic-range data indicate that it is a shock formed by a recompression as the flow turns around the body of the command module. They recommended that the entire positive phase be used when extrapolating the near-field signatures to the far field.

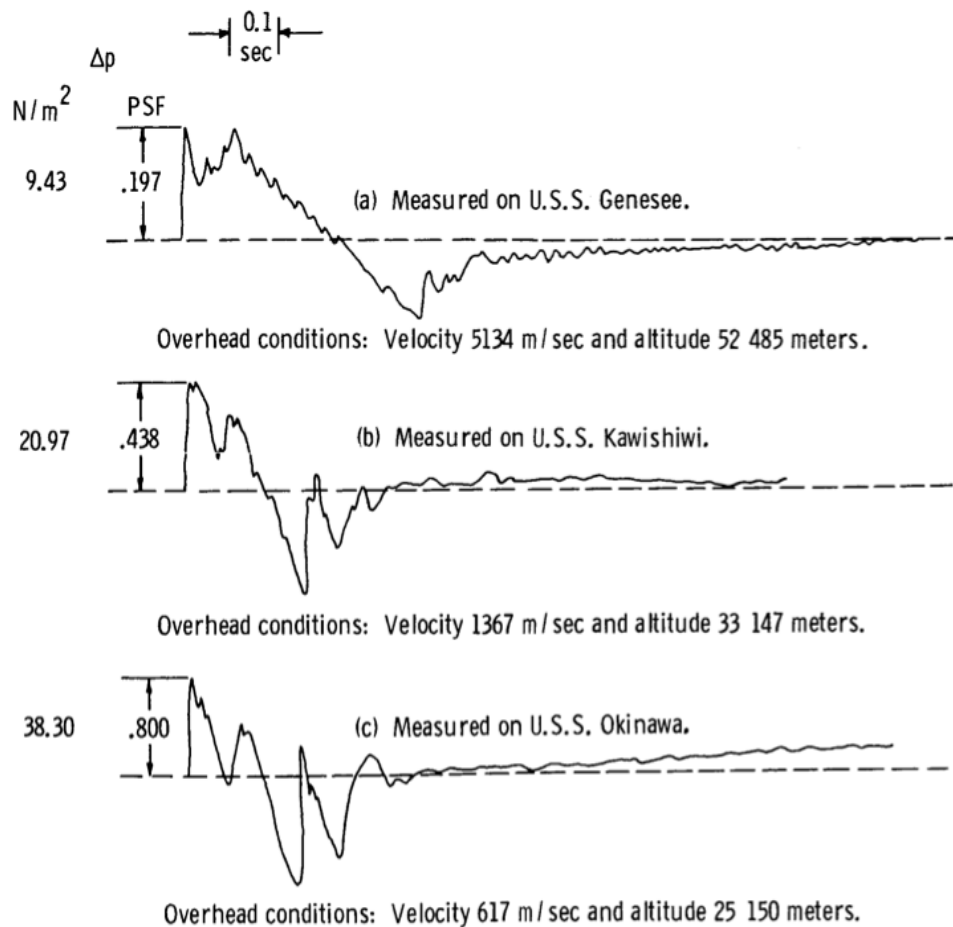


Figure 2.21 Apollo 15 capsule reentry sonic boom waveforms measured at three distances from the splashdown location. Approximate capsule velocity and altitude are indicated for each waveform at the time the capsule was directly overhead, which are not the same as the conditions at which the sonic boom was generated. Adapted from Fig. 14 in Hilton *et al.* (1972).

Hicks *et al.* (1972a) used wind tunnel measurements of the Apollo command module to predict peak overpressure values from the reentry of Apollo 15 (Hilton *et al.*, 1972). The purpose was to extend the conditions for which sonic boom prediction methods could be applied, with a particular emphasis on the peak overpressure. They used the wind tunnel data of Mendoza and Hicks (1971) and the signature extrapolation method of Thomas (1971). To determine the source conditions corresponding to actual measured data, they iteratively tested different ray paths until they found one that was within 100 m of each ship, stating that there was little variability once within 100 m of the ship locations. Although they had measured atmospheric wind data, these data came from more than 300 miles away, and they opted to instead assume zero wind at all altitudes. Overall,

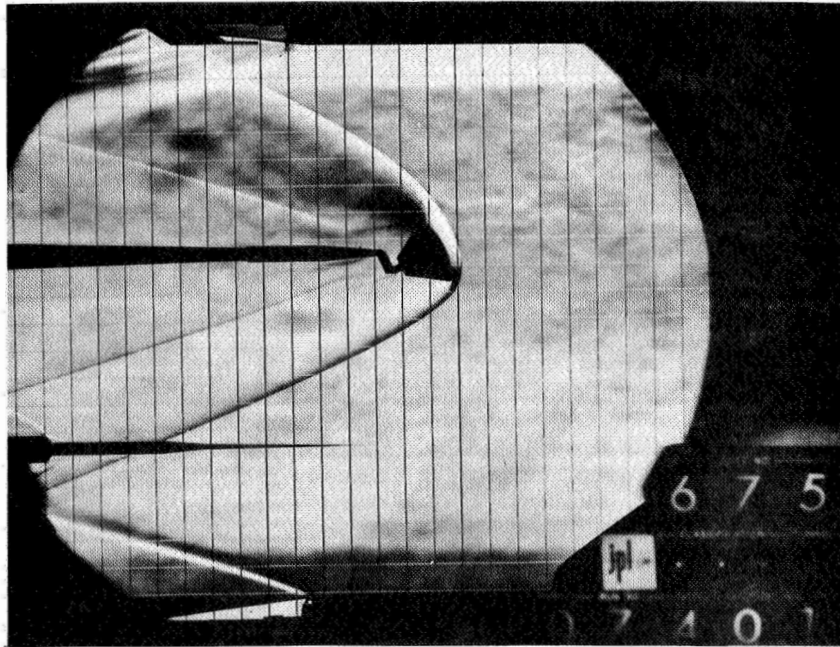


Figure 2.22 The 0.016-scale Apollo command module in the wind tunnel at Mach 3.20. Figure reproduced from Mendoza and Hicks (1971).

they predicted the peak overpressure for the signature generated at Mach 4.57 to within 0.02 psf and the peak overpressure for the signature generated at Mach 1.16 to within 0.16 psf. They noted that their assumption of zero wind likely impacted the Mach 1.16 measurement more. Although a third ship made measurements, the signature was generated at Mach 15.65, which was well beyond the highest Mach number of 7.75 used in the wind tunnel tests at the required bank angle and was therefore omitted from the analysis. The authors also noted that while the peak overpressure predictions were good, the predicted waveforms were N-waves while the measured waveforms had several intermediate shocks as was noted also by Hilton *et al.* (1972). They provided a few possible explanations, including differences between the wake produced in the wind tunnel and in actual flight, the wind tunnel sting removing extra shocks associated with the backward-facing step at the top of the command module in flight, and possible shock reflections from the ships at sea.

A similar study was performed for Apollo 16 (Garcia *et al.*, 1973). They used the wind tunnel measurements of both Mendoza and Hicks (1971) and Hicks *et al.* (1972b). The near-field signatures were first extrapolated using the strong shock theory of Hicks *et al.* (1972b) and then the waveform parameter method of Thomas (1972) once the shocks were sufficiently weak. When recording the sonic booms at sea (Henderson and Hilton, 1974a) two ships were used. One of the ships had a single microphone while the other had seven deployed in various locations around the ship, including two above the mast. Other details of the prediction methods were similar to Hicks *et al.* (1972a) for Apollo 15, including the assumption of zero wind speed throughout the atmosphere. The predicted and measured results have been digitized from the report and compiled in Fig. 2.23. While the

agreement for the peak overpressures is excellent, Garcia *et al.* (1973) stated that the origin of the additional features in the measured waveforms are not yet satisfactorily explained and provided the same potential explanations as Hicks *et al.* (1972a).

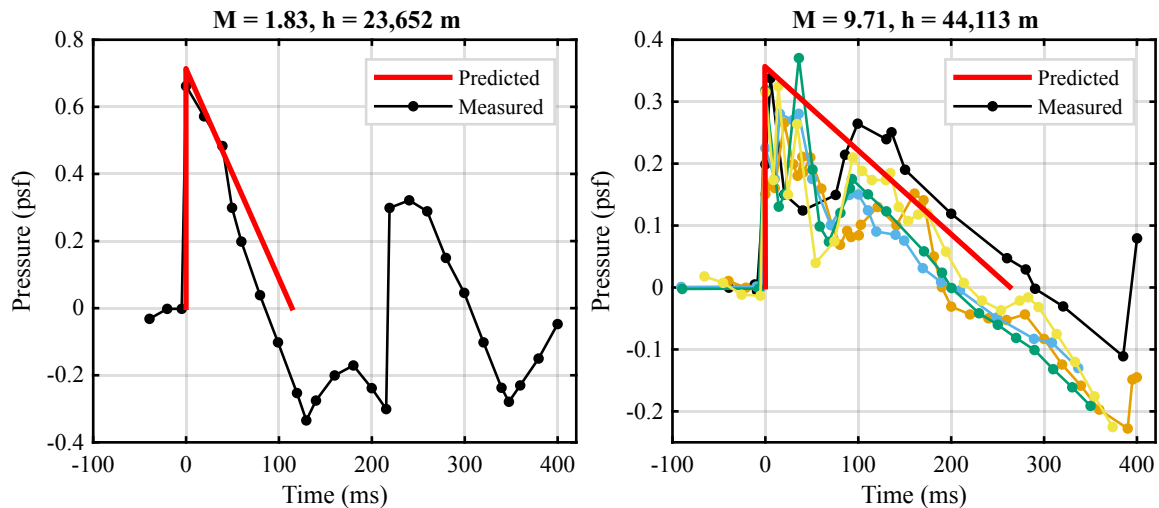


Figure 2.23 Predictions and measurements for the Apollo 16 command module reentry sonic boom measured aboard two ships in the Pacific Ocean. The data have been digitized and reproduced here from Garcia *et al.* (1973). One ship (right) had five microphones located at deck level, all of which are shown.

2.4.2 Space Shuttle

Measurements

Measurements of the STS-1 reentry sonic boom were reported across a few different reports (Garcia *et al.*, 1982, 1983a, 1985; Garcia and Potter, 1983; Potter, 1983). The primary goal was to validate the prediction methods used for the Space Shuttle program. Eleven measurement locations were placed along the approximate ground track in California, as shown in Fig. 2.24. These measurement locations were selected based on the envelope of Mach numbers for which wind tunnel data were available (Mendoza, 1975b; Ashby, 1979). Each measurement station used three ground-based microphones and a single elevated microphone at simulated ear height. The measured waveforms for one ground-based microphone at each station are shown in Fig. 2.25. Overall, the measured overpressures were near the predicted values. Figure 2.25 also indicates the approximate Mach number and altitude at which the sonic booms were generated corresponding to each measurement location. These conditions were calculated using iterative ray tracing until a ray was found that landed near the measurement location. There is a clear trend for the signature duration to be longer for higher Mach numbers and altitudes. The overpressure was observed to increase with decreasing Mach number and altitude. The authors also discuss the longer duration for these sonic booms when

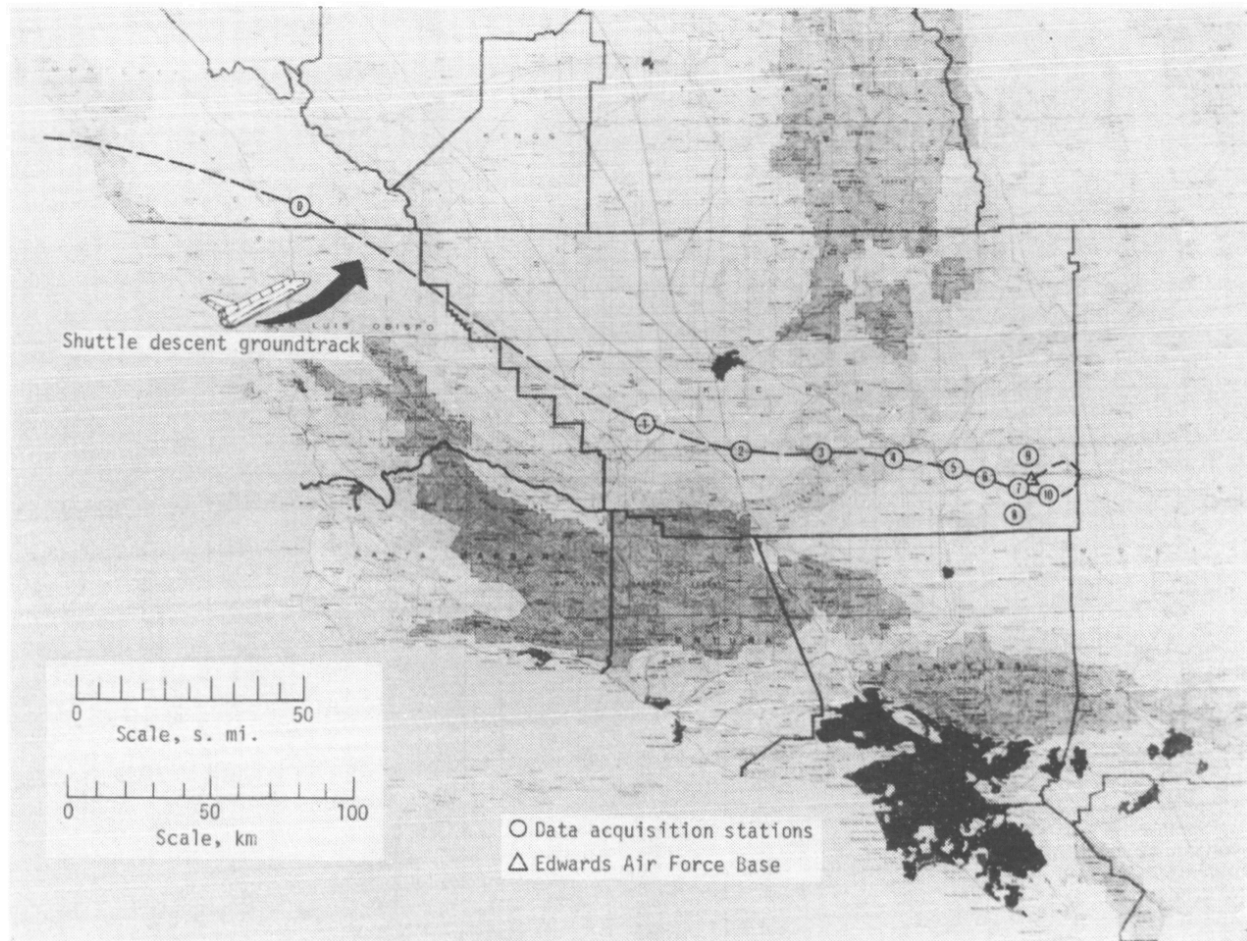


Figure 2.24 STS-1 reentry sonic boom measurement locations. Figure reproduced from Garcia *et al.* (1985).

compared to traditional aircraft. For predictions, a ground reflection factor of 1.9 had been applied to the waveforms. The elevated microphones at each station were also used to estimate a ground reflection factor, which was determined to vary from 1.83–2.32 depending on the measurement location.

Further measurements were made during the STS-2 reentry (Garcia and Potter, 1983; Potter, 1983). For STS-2, the four measurement stations were located in the anticipated region of highest overpressure under the flight track. The four locations measured overpressures of 1.44, 2.28, 1.74, and 2.16 psf, averaging about 10% lower than predictions. This is opposite to the trend for STS-1, where the measurements were about 10% higher than predictions.

Measurements made during the STS-4 mission were aimed at capturing the region near the lateral cutoff (Garcia and Potter, 1983; Potter, 1983). With increasing distance from the ground track, the stations measured overpressures of 0.94, 0.88, 0.28, and 0.06 psf. It was concluded that the

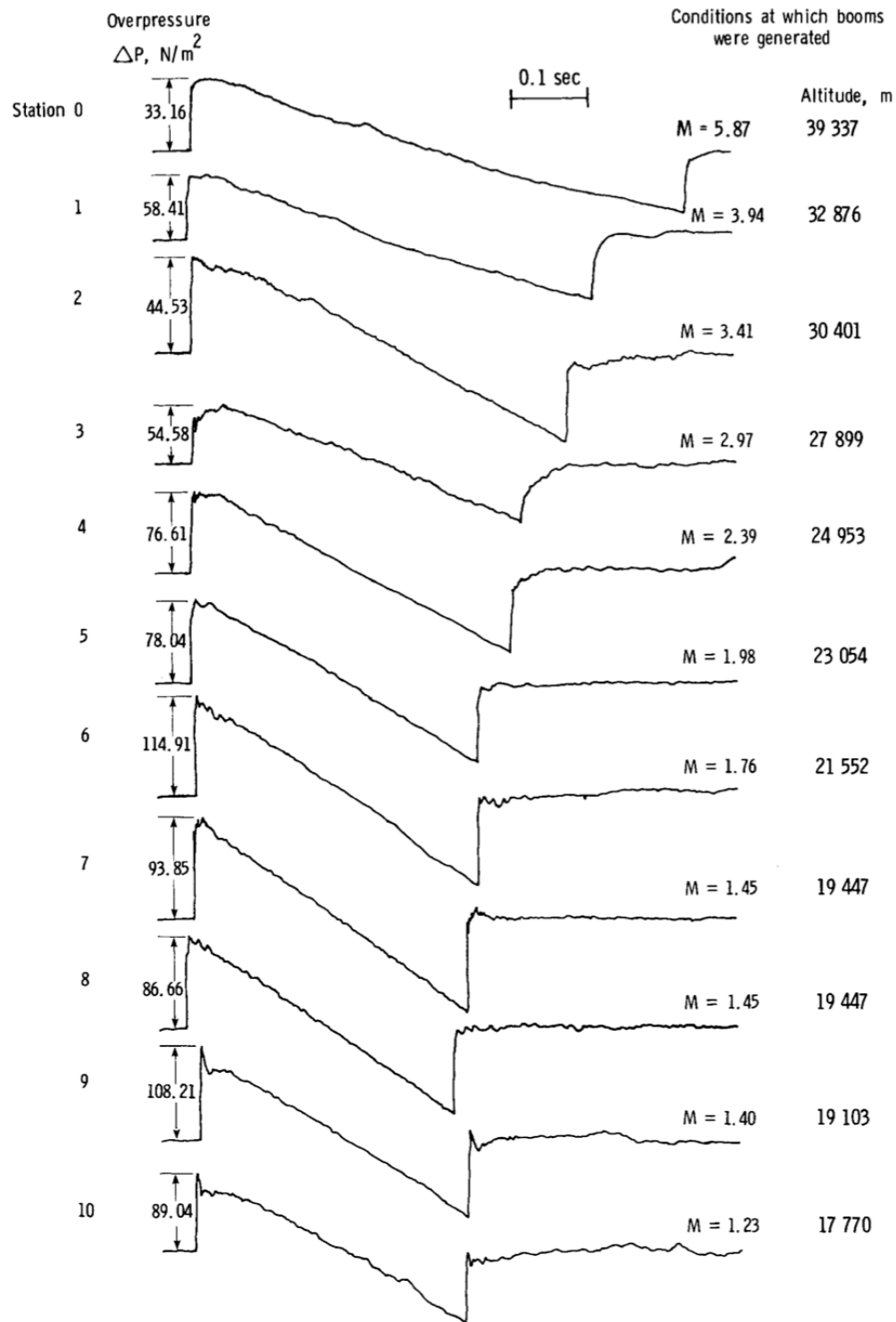


Figure 2.25 Measured STS-1 reentry sonic boom waveforms. Figure reproduced from Garcia *et al.* (1985).

lateral cutoff occurred near the 0.06-psf measurement. Predictions had been made using pre-flight trajectory and weather data, and disagreed with the measurements, predicting an overpressure of 0.62 psf at the station that measured 0.06 psf. Garcia and Potter (1983) stated that this was likely to be resolved when using post-flight trajectory and weather data.

Much of the remaining publicly-available information regarding Space Shuttle reentry sonic booms comes from a summary report by Maglieri *et al.* (2011). They provided long tables giving details about which sonic booms were measured and what their properties were. However, no definitive location information is given for the different measurement channels, limiting the analyses that can be done using their tables. Maglieri *et al.* (2011) do state that much of the data can be found in a supplemental download, but it is not publicly available at this time.

Modeling

In the early design phase of the Space Shuttle, there were multiple different design propositions. Because different designs could impact the reentry sonic boom, studies were carried out to assess the sonic boom from a low cross range vehicle (Levy *et al.*, 1993) and a high cross range vehicle (Hicks *et al.*, 1993). Although these reports were officially published in 1993, evidence within the reports suggest they were written between 1969–1971 because one of the reports cites research from 1969 and neither make mention of extrapolation of wind tunnel signatures via the methods of Thomas (1971, 1972) that rapidly became commonplace. Both analyses used wind tunnel data, extrapolated via the methods of Hicks and Mendoza (1967), to predict ground-level sonic booms. The low cross range vehicle was tested only at an angle of attack of 60° and predicted to have an overpressure of about 2 psf on the ground, and Levy *et al.* (1993) stated that this would likely be unacceptable for populated areas. The high cross range vehicle was studied using a few different conditions. Wind tunnel measurements were made at both 25° and 60° angle of attack, and both angles of attack had different assumed trajectories through the atmosphere. Hicks *et al.* (1993) reported that the overpressure from the 25° angle of attack would be below 1.0 psf at all Mach numbers while 60° would result in an overpressure between 0.9–1.4 psf, depending on the Mach number. It was assumed that the 60° angle of attack would therefore produce sonic booms that would be unacceptable on the ground. Recognizing the need to determine whether the differences in the two angles of attack were caused by their angles or their trajectories, they also calculated the overpressures from the 25° angle of attack as if it were flying along the trajectory that the 60° angle of attack vehicle would take. Clearly, this is not physical as the trajectory is related to the angle of attack, but it provided a useful test. They found that the 25° angle flying along the different trajectory still produced overpressures that were less than 1.0 psf at all Mach numbers and were similar to those of the original trajectory. Thus, Hicks *et al.* (1993) concluded that a trajectory change is less likely to impact the overpressure than an angle of attack change. They also stated that the effects of bank angle, its derivative, and the heading angle derivative needed further study.

There were many different possible trajectories for the Space Shuttle reentry flight path, depending on the mission. McDonough (1975) investigated the sonic boom from a "Mission 3B", which called for a northerly return down into VAFB. Predictions were made using the method of Thomas (1972). There was a region near VAFB, nearly from Santa Maria down to Lompoc, that was expected

to receive an overpressure greater than 2 psf. This had been deemed unacceptable in the 1972 environmental impact statement for the Space Shuttle (NASA, 1972, Not Publicly Available). They also found that certain trajectory maneuvers, like S-turns, could lead to focusing on the ground. To bring the peak overpressures down closer to 2 psf, McDonough (1975) determined flight parameter boundaries that reduced the overpressures on the ground.

Glatt *et al.* (1975a) used wind tunnel data, coupled with the method of Thomas (1971), to perform optimizations on the Space Shuttle reentry trajectory to reduce the peak overpressures at the ground. While they used a delta-wing orbiter design that did not match the final Shuttle design, they stated that the results should still be reasonably close to those from the final design as long as the angles of attack are sufficiently high. They used wind tunnel data to produce a database of pressure signatures (Glatt *et al.*, 1975b) that could then be interpolated to estimate pressure signatures in between test conditions. In limited cases, extrapolation was also performed. They found that the Space Shuttle sonic boom peak ground overpressures were produced toward the end of the flight where the altitude and Mach number were lower, rather than the higher-velocity regime where the altitude and Mach number were both higher. They found that the ground overpressure could be reduced by strategically increasing the vehicle angle of attack at the right time to loft the vehicle higher and decrease the Mach number. Using various optimization schemes, Glatt *et al.* (1975a) were able to reduce the peak modeled ground overpressures from 1.74 psf to 1.31 psf.

Cour-Palais (1977) presented proceedings of the 1976 Space Shuttle Environmental Assessment Workshop on Tropospheric Events. Modeling was performed for the anticipated OFT-1 mission, which called for a 30–40° angle of attack at reentry, with a gradual pitching down to 13° between speeds of 3,200 m/s and 760 m/s. The vehicle was expected to pass over land at Mach 5.6. It was found that the highest overpressures over land were expected to be 2.1 psf, and that these overpressures would occur over relatively unpopulated areas. They stated that the overpressure of 2.1 psf was less than would have been predicted using a previous trajectory design. The peak overpressures expected in more-populated areas were between 0.8–1.0 psf. Brief mentions were also made regarding the SRB and external fuel tank sonic booms when reentering the atmosphere, but little to no research had been performed.

Mendoza (1975b) performed wind tunnel measurements on a 0.0041-scale model Space Shuttle orbiter that closely resembled the final design (see Fig. 2.26). The measurements were made from Mach 1.30–3.02 and the angles of attack were varied between 10° and 25°. Direct comparisons were made to a previous delta-wing orbiter design by using wind tunnel data to propagate signatures to the ground from both the latest and the previous design when flying along two different trajectories. The updated design was determined to produce higher overpressures on the ground over the range of conditions considered. A separate comparison using data from Hicks *et al.* (1971) included tests performed with straight-wing and delta-wing orbiter designs at 60° angle of attack to demonstrate that differences in vehicle geometry matter less at high angles of attack when considering the sonic boom. Mendoza (1975b) also cited reports by Hicks and Mendoza (1971b) and Hicks and Mendoza (1972, Not Publicly Available) that discussed wind tunnel data for a delta-wing orbiter design.

Carlson and Mack (1978) set out to determine whether far-field sonic boom theory could be successfully applied to the Space Shuttle reentry sonic boom. As the Space Shuttle had not yet started flying, their study was performed using wind tunnel data. To provide enough distance in

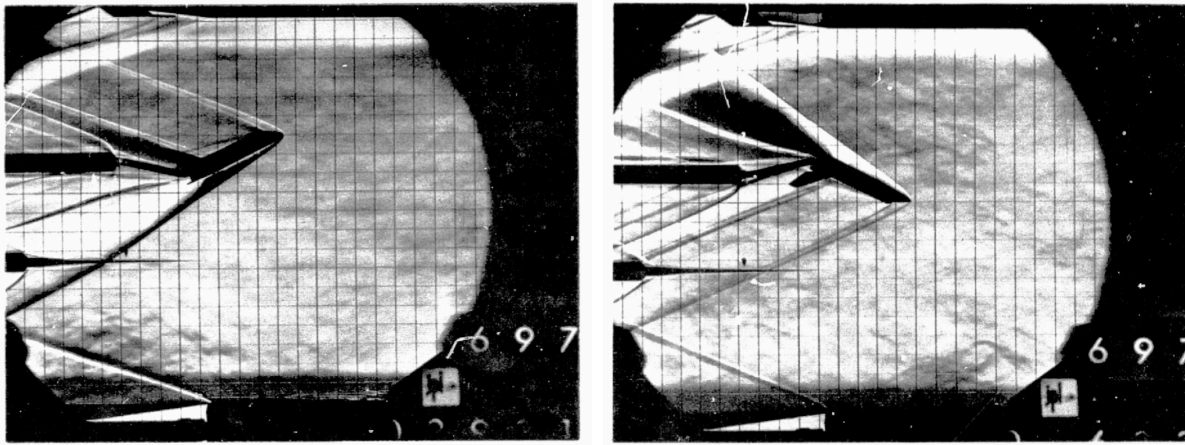


Figure 2.26 Wind-tunnel experiments on the Space Shuttle orbiter in its reentry configuration. The pressure field was measured at different azimuthal angles including 0° (Left) and 180° (Right). Images from Mendoza (1975b).

the wind tunnel for the sonic boom pressure signature to reach the far field, they used a very small 0.0004-scale model for which the relative size of the wind tunnel was sufficiently large to approach far-field conditions for some measurements. They performed tests at two Mach numbers (2.8 and 4.14) and three angles of attack (0.3° , 19.0° , and 41.0°). Although some conditions, especially at higher angles of attack and Mach numbers, did not reach far-field conditions, they were able to extrapolate those measurements to approximate the far-field conditions. In their theoretical analysis, they recommended that the area distribution representing the vehicle be calculated normal to the freestream rather than along Mach lines because the blunt vehicle produces a detached bow shock and the area normal to the freestream appears more appropriate. Overall, they found good agreement with theory for both the peak overpressure and signature impulse, while the signature duration was off by as much as 20%. They concluded that simple theoretical methods like those of Carlson (1978) can provide reasonably accurate estimates for far-field sonic boom signatures from spacecraft on reentry. An important future step they recommended is to compare theoretical estimates with Space Shuttle flight-test data.

Ashby (1979) performed wind tunnel measurements for a 0.0041-scale Space Shuttle orbiter at Mach 6. The tests were performed between angles of attack of 10° and 40° . A finite-difference computer code was used to calculate the expected pressure signature at the same distance from the vehicle as the wind tunnel measurements. The computer code agreed well with measurements when considering the total area under the pressure signatures at 25° and 30° angle of attack. Ashby (1979) concluded that the computer code was validated and that theoretical estimates could replace much of the future wind tunnel work.

Sonic booms from the Space Shuttle orbiter, SRBs, and external fuel tank are briefly mentioned in the environmental impact statements for the Galileo and Ulysses missions (NASA, 1988, 1989). After being jettisoned, the SRBs would land in the ocean downrange of the launch site and were

anticipated to produce overpressures as high as 2–3 psf. A focus region was also expected 240–320 km downrange of the launch site. The external fuel tank was expected to produce sonic booms over the Indian ocean with overpressures as high as 2–4 psf.

2.4.3 Other Vehicles

Stardust Comet Sample Probe

Plotkin *et al.* (2006a) predicted and measured the reentry sonic boom from the Stardust comet sample probe in January 2006. They determined an effective F-function based on the work of Tiegerman (1975) and propagated the signature using PCBoom 4. They predicted the peak overpressure to be 0.0524 psf and measured it to be 0.052 psf. They predicted the arrival time to be 10:00:28.465 UTC and it arrived at 10:00:29.719 UTC.

OSIRIS-REx Sample Return Capsule

Bishop *et al.* (2025) performed modeling on the OSIRIS-REx sample return capsule, which returned to Earth in September 2023. This return capsule had identical exterior dimensions to the Stardust comet sample probe. Measurements were performed using infrasound sensors. They characterized all arrivals as N-waves with amplitudes ranging from 0.038–0.056 psf and positive phase durations of 0.138–0.160 s. Waveform modeling was performed using Whitham’s far-field theory (Whitham, 1952), Carlson’s simplified sonic boom prediction method (Carlson, 1978), and Tiegerman’s drag-dominated hypersonic model (Tiegerman, 1975). Overall, they found that accurate results could be obtained using the Carlson approach, but that overall the Tiegerman model better matched measured data. However, although the overpressures were well-predicted by the Carlson and Tiegerman models, the modeled durations were longer than the measured values.

Generic Blunt Bodies

Carlson and Mack (1977) recognized that the linear sonic boom theories of Whitham (1952) and Walkden (1958) had been highly successful in predicting sonic boom properties in the far field. However, when applied to high Mach numbers and blunt bodies, the assumptions underlying those theories are not valid. Rather than accept the limitations of these theories directly, Carlson and Mack (1977) decided to test the applicability of these theories to blunt bodies at high Mach numbers that would be representative of spacecraft entering the atmosphere and exhaust plumes behind rockets on ascent. To this end, they performed wind tunnel measurements at Mach 4.14 on blunt paraboloid objects (with two different scaled sizes) and measured the pressure signatures at normalized distances of 2, 4, 8, 16, and 32 body lengths away from the model. Although far-field conditions were not fully met at the 32-body-length distance, they were able to extrapolate their data and determine whether the far-field theory would be approached. They found that the peak overpressure tended to asymptotically converge to the theoretical far-field value within 256 body lengths. The impulse and signature duration both appeared to approach the theoretical values, but more slowly. Extrapolation beyond 256 body lengths was not performed.

Ashby (1980) performed follow-up analyses to Carlson and Mack (1977) using the same geometry at Mach 6. He used the method of Ferri *et al.* (1976) to extrapolate the wind tunnel measurements at 2 body lengths to the far field (at least 512 body lengths) for comparison with what the linearized far-field theory alone would predict. The peak overpressure was accurately predicted by the linearized far-field theory, while the impulse and signature duration were both overestimated by the linearized far-field theory. This validated the overpressure results of Carlson and Mack (1977) while clarifying that the linear methods were not expected to be accurate for signature duration and impulse for blunt bodies at high Mach numbers. Along with these analyses, Ashby (1980) validated a finite-difference computer code for predicting sonic boom overpressures at the Mach numbers used.

Sounding Rockets

Sounding rocket flights in 2004 enabled a reentry sonic boom measurement from the descending rocket. The sonic boom was studied by Plotkin *et al.* (2006b) and found to be an N-wave with a peak overpressure of 0.2 psf. The low-amplitude N-wave was used to validate computer models for shock structure due to atmospheric propagation.

2.5 Response to Sonic Booms

2.5.1 Structures

The effects of sonic booms on structures has been researched since at least the late 1950s (ARDE Associates, 1959). A literature review covering the early research was provided by Hubbard (1966). One of the useful graphics included in his paper is reproduced Fig. 2.27, which demonstrated why structures are affected by sonic booms. Starting from the left, as the positive portion of the sonic boom first touches the structure, the net force on the structure points to the left. A moment later, when the structure is entire engulfed by the positive phase of the sonic boom, the pressure pushes inward from all sides. The opposite occurs once the negative phase of the sonic boom passes over the structure, where the negative pressure “pulls” outward from all sides. Lastly, as the negative phase finishes passing over the structure, the net force is to the left again. All these different loadings can excite a transient response from the structure.

The processes by which the sonic boom energy couples to the structure and produces additional vibrations and sounds is complex and highly dependent on the structure and sonic boom details. However, a simple example is shown in Fig. 2.28 (originally from Hubbard (1966)) showing the signature measured outdoors followed by the pressure response measured inside the building, the perceptible acoustic noise, and the acceleration on one of the surfaces.

An important finding relating to structural response is that the response depends not just on the overpressure, but also on the waveform shape as discussed by Cheng and Benveniste (1969) (see also Clarkson and Mayes (1972) and references therein). They analyzed this problem in terms of the dynamic amplification factor (DAF), which is a normalized measure of how much response is

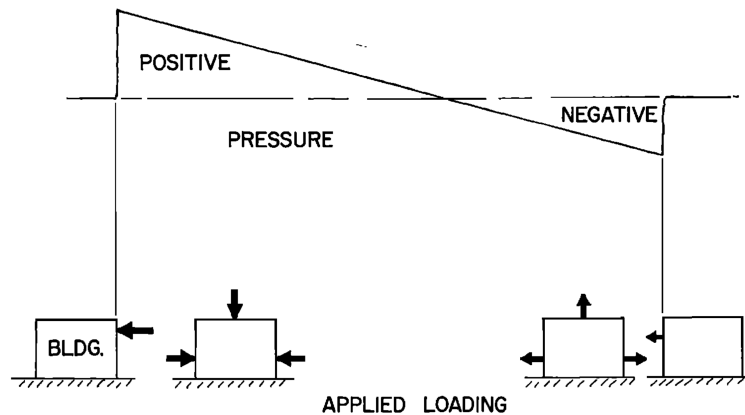


Figure 2.27 Graphical depiction of the pressure loading on a generic building. Figure reproduced from Hubbard (1966), where it may have been reproduced from another, earlier, reference that appears to not be publicly available. Reprinted with permission from Hubbard, H. H. (1966). "Nature of the Sonic-Boom Problem," *J. Acoust. Soc. Am.* 39(5B), S1-S9, DOI:10.1121/1.1914037. Copyright 1966, Acoustical Society of America.

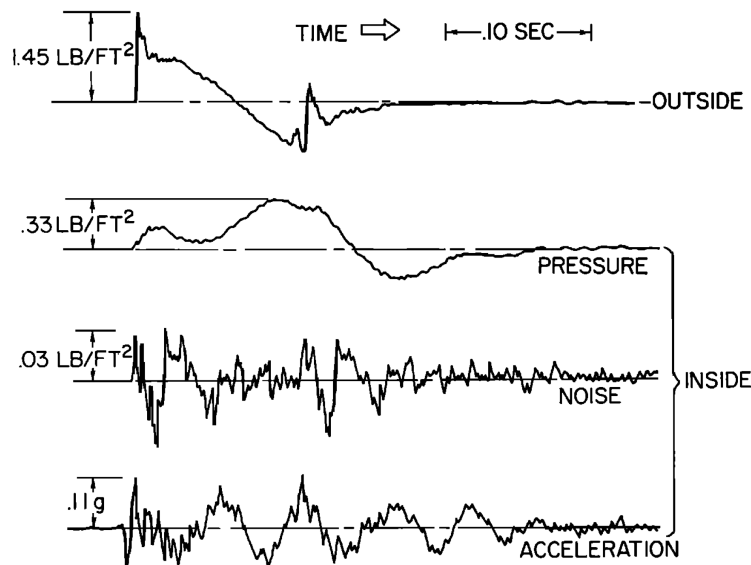


Figure 2.28 Examples of how a sonic boom signature changes after propagating into a structure and the acoustic and vibratory effects it has on the interior. Reproduced from Hubbard (1966). Reprinted with permission from Hubbard, H. H. (1966). "Nature of the Sonic-Boom Problem," *J. Acoust. Soc. Am.* 39(5B), S1-S9, DOI:10.1121/1.1914037. Copyright 1966, Acoustical Society of America.

produced by the dynamic load relative to a static load. The results for four different waveform shapes on a single-degree-of-freedom system are shown in Fig. 2.29. Notice that the system responds differently to each waveform. This dependence on waveform shape is supported by the results of Klos and Buehrle (2007). Figure 2.30 shows sonic booms produced using two different flight profiles. Each flight profile generated two booms that arrived within a couple seconds of each other. This expands on the work of Cheng and Benveniste (1969) by showing that waveform shape (even with comparable overpressures) matters in a full-scale environment. The plots on the left were generated with the vehicle in level flight, with the first signature being the main carpet signature and the second a late post-focus boom. As expected, the main signature produces a larger response on the wall's acceleration than the smaller signature does. On the right, a dive maneuver was used that produced two booms with comparable overpressure. The first is an N-wave and the second is a U-wave. Although the overpressures are similar, the U-wave results in a larger acceleration response from the wall. However, this is not always necessarily the case. For example, Klos and Buehrle (2007) also showed the results from a window-mounted accelerometer (not shown in Fig. 2.30) that showed comparable accelerations produced from both the N-wave and the U-wave. Thus, although waveform shape matters, the response of different components from a single boom is not a simple problem.

Haber and Nakaki (1989) performed an extensive literature review on sonic boom damage to conventional structures. The results of this literature review are shown in Tables 2.5 and 2.6. These same results have been displayed similarly in other reports (FAA, 1998, for example), but the results are often abbreviated, presumably for simplicity. Tables 2.5 and 2.6 show the full comments from Haber and Nakaki (1989) with only minor changes.

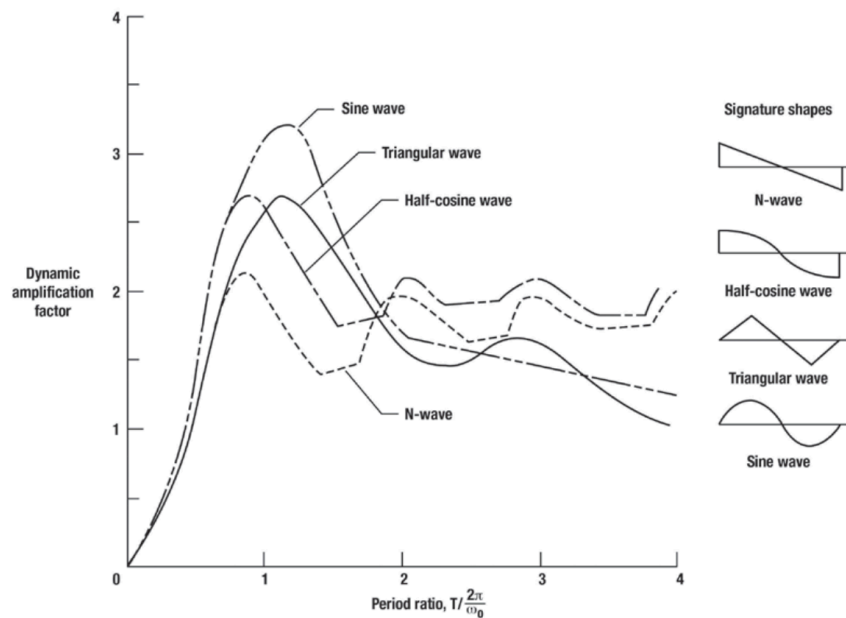


Figure 2.29 Dynamic amplification factors (DAF) for different waveform shapes for a single-degree-of-freedom system. The DAFs are shown as a function of their period. Reproduced from Maglieri *et al.* (2014), who say it is adapted from Clarkson and Mayes (1972) and Cheng and Benveniste (1969). The data appear to come from Clarkson and Mayes (1972) and a similar plot, though not with identical data, is found in Cheng and Benveniste (1969).

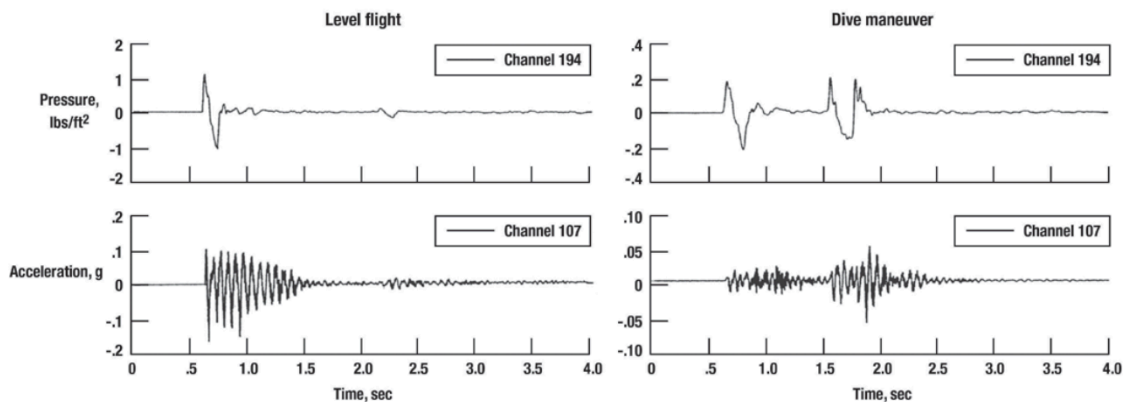


Figure 2.30 Pressure waveforms measured outside (top left and right), compared with the acceleration measured by a wall-mounted accelerometer (bottom left and right). Reproduced from Maglieri *et al.* (2014), which was adapted from Klos and Buehrle (2007).

Table 2.5 Damage from sonic booms between 0.5–4 psf. Source: Haber and Nakaki (1989) Table 2-1.

Overpressure	Items Affected	Details and Supporting Remarks
0.5–2 psf	Cracks in plaster	- Fine; extension of existing; more in ceilings; over door frames; between some plaster boards. - Areas of lath/plaster. Ceilings at 2 psf. - The bulk of these types of ‘damages’ is in private houses where fragile objects, friable plaster and glass are widespread.
	Cracks in glass	- Rarely shattered; either partial or extension of existing. - Glass in rusty frames very vulnerable; can fail at 1 psf (prior faults obvious).
	Damage to roof	- Slippage of existing loose tiles/slates; sometimes new cracking of old slates at nail hole. - Older-type roofs can slip partially or wholly. Confined to roofs when excessive nail corrosion; especially slurry wash roofs. - Modern buildings and industrial complexes are rarely affected.
	Damage to outside walls	- Existing cracks in stucco extended. - Old and tall double stone walls can collapse. Always due to prior excessive damage to rubble core. - Stained glass windows not affected unless in very bad condition already.
	Bric-a-brac	- Those carefully balanced or on edges can fall; fine glass, e.g., large goblets.
	Other	- Dust fall in chimneys - Blockage of ducts previously unswept - smoke damage.
2–4 psf	Glass, Plaster, Roofs, Ceilings	- Failures show which would have been difficult to forecast in terms of their existing localized condition. Nominally in good condition. - Glass: Worst of these failures, will be caused by a combination of good dynamic coupling and lower-bound (statistical) strength. No glass flying. - Plaster: Nearly always due to acoustic coupling between the sonic boom and the roof space. Bungalows vulnerable. - Roofs: Breakage of eroded but otherwise effective nails/pegs. - Ceilings: Clean breaks in plaster board joints especially in bungalows (coupling effect).

Table 2.6 Damage from sonic booms between 4–10 psf and higher. Source: Haber and Nakaki (1989) Table 2-1.

Overpressure	Items Affected	Details and Supporting Remarks
4–10 psf	Glass	- Regular failures within a population of well-installed glass; industrial as well as domestic; green houses; ships; oil rigs; - Some glass will fail either to dynamic coupling alone or lower-bound strength alone. Glass pieces can drop out; some flying;
	Plaster	- Partial ceiling collapse of good plaster; complete collapse of very new, incompletely cured or very old plaster. - Roof space dynamic coupling.
	Roofs	- High probability rate of failure in nominally good state, slurry-wash; some change of failures in tiles on modern roofs; light roofs (bungalow) or large area can move bodily. - Slates/tiles damaged by bounce (acceleration more than 1 g). Large roofs lifted by negative overpressure part of sonic boom waveform.
	Outside Walls	- Old, free-standing walls in fairly good condition can collapse. - The usual requirement is for the boom wave front to be normal.
	Inside Walls	- ‘Party’ walls known to move at 10 psf. - Usually due to acoustic coupling in the room.
>10 psf	Glass	- Some good glass will fail regularly to sonic booms from the same direction. Glass with existing faults could shatter and fly. Large window frames move. - Due to forced response: (a) edge failures - frame impact; (b) center failures - mass stress mode.
	Plaster	- Most plaster affected.
	Ceilings	- Plaster boards displaced and nail popping. - Large ceiling movements especially in bungalows.
	Roofs	- Most slate/slurry roofs affected, some badly; large roofs having good tile can be affected; some roofs bodily displaced causing gable-end and wall-plate cracks; domestic chimneys - dislodgment if not in good condition. - Chimneys are not easily affected because they don’t couple well with sonic boom characteristics.
	Walls	- Internal party walls can move even if carrying fittings such as hand basins or taps; secondary damage due to water leakage. - Mainly due to room acoustic coupling
	Bric-a-brac	- Some nominally secure items can fall, e.g., pictures; especially if fixed to party walls.

2.5.2 Humans

Research into the subjective perception of sonic booms has taken place since the 1960s (Zepler and Harel, 1965), and a thorough literature review is provided by Maglieri *et al.* (2014). Among the important findings has been that the properties (overpressure and rise time) of the shocks are very important to determining subjective loudness (Niedzwiecki and Ribner, 1978; Shepherd and Sullivan, 1991). In particular, it was found that two sonic booms could have equal overpressures but be perceived differently based on the shock rise time and other fine-scale details of the shock structure. These findings led to the determination of a handful of metrics that correlated with human response (Loubeau and Page, 2018). These metrics include the A-, B-, D-, and E-weighted sound exposure level (SEL) along with the Indoor Sonic Boom Annoyance Predictor (ISBAP) and the Perceived Level (PLdB/PL). The most-commonly used among these is the PL, which is based on the Steven's Mark VII Perceived Level of Loudness (Stevens, 1972).

Although sonic boom signatures share many properties with other phenomena like thunder (Ribner and Roy, 1982) and fireworks (Maglieri and Henderson, 1973), Maglieri *et al.* (2014) noted that these events can all elicit startle responses from observers. They also noted that in field measurements where the sonic boom arrival time is predicted to within one second, observers are still startled. Thus, they concluded that startle is inherent for impulsive-type sounds.

From July 1961 to April 1962, about 150 sonic booms were produced near St. Louis, Missouri to study how people would respond (Nixon and Hubbard, 1965; Nixon and Borsky, 1966). Similar studies were performed in Oklahoma City, Oklahoma from February to July 1964 (Hilton *et al.*, 1964; Borsky, 1965). In the St. Louis study, where the peak overpressures were about 3.1 psf, most interviewees stated that the sonic booms had some interference with their daily activities. Despite this, less than 1% of them submitted complaints (Nixon and Borsky, 1966). In the Oklahoma City tests, where the peak overpressures were about 1.2 psf, most people stated that they believed they could learn to live with the sonic booms. There were, however, “substantial” numbers of people in the Oklahoma City tests who claimed that the sonic booms interfered with their daily activities (Borsky, 1965). The types of interference found in the St. Louis and Oklahoma City studies were compared by Brown and Sutherland (1992) and shown in Fig. 2.31. Among these different categories, people appear to have responded the most to their house shaking and to being startled.

When considering rattle, Schomer (2004) states that “[o]ne cannot overestimate the role that noise-induced rattle plays in sonic boom and blast noise annoyance. The earliest sonic boom researchers found this, and it is primarily the auditory perception of the rattles that is the issue.” He made a direct comparison between annoyance reports from artillery noise and street traffic. Rattle was by far the most-reported source of annoyance for the impulsive noises, even greater than startle.

There have been many other studies on the impacts of sonic booms. A literature review is available in Chapter 8 of Maglieri *et al.* (2014) and contains additional information on sleep disturbance, human health, wildlife, and seismic effects.

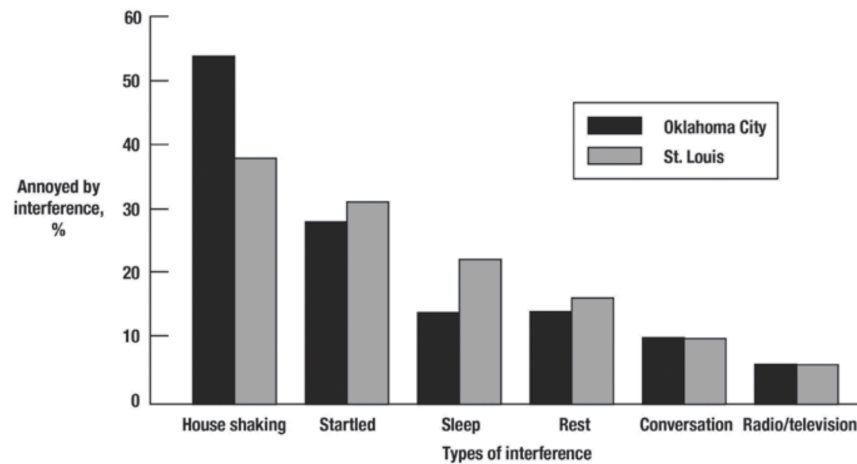


Figure 2.31 Different interference types for two measurement campaigns. Peak Oklahoma City sonic booms were 1.2 psf and peak St. Louis booms were 3.1 psf. Reproduced from Maglieri *et al.* (2014), which was adapted from Brown and Sutherland (1992).

2.6 Conclusion

Research into rocket sonic booms began in earnest as the Space Shuttle program progressed. It was recognized that an accurate model for high-altitude, high-Mach-number flight for blunt bodies was needed. This model was beyond the validation cases of previous models for airplanes. Measurement and modeling efforts for rockets ensued during the Apollo program. Once validated, the models were applied to the Space Shuttle. The models work well for predicting peak overpressure values for rocket sonic booms along the ground track, but little validation has been done off the ground track. Despite the success of these models, much work remains to be done on rocket and spacecraft sonic booms, as discussed in Sec. 1. Such work is the focus of this dissertation and much will be discussed in the chapters that follow.

Although not the focus of this dissertation, some effects of sonic booms on structures and humans have been discussed. In general, sonic booms can couple with building structures to vibrate and potentially damage windows and interior walls. Outdoors, humans respond primarily to the details in the shocks themselves. Indoors, humans are more likely to be annoyed by low-frequency-induced rattle and the startle they experience from the impulsive sound.

Part I

Sonic Boom Measurement Challenges

Chapter 3

Reducing Contaminating Noise Effects in Sonic Boom Metrics

Abstract

¹During NASA X-59 quiet supersonic aircraft community response tests, low-boom recordings will contain contaminating noise from instrumentation and ambient acoustical sources. This noise can inflate sonic boom perception metrics by several decibels. This chapter discusses the development and comparison of robust lowpass filtering techniques for removing contaminating noise effects from low-boom recordings. The two filters are a time-domain Butterworth-magnitude filter and a frequency-domain Brick Wall filter. Both filters successfully reduce noise contamination in metric calculations for simulated data with real-world contaminating noise and demonstrate comparable performance to a modified ISO 11204 correction. The Brick Wall filter's success indicates that further attempts to match boom spectrum high-frequency roll-off beyond the contaminating noise floor are unnecessary and have marginal improvements on final metric calculations. Additionally, the Butterworth filter removes statistical correlation between ambient and boom levels for a real-world flight campaign, adding evidence that these techniques also work on other boom shapes. Overall, both filters can produce accurate metric calculations with only a few hundred hertz of positive signal-to-noise ratio. This work describes methods for accurate metric calculations in the presence of moderate noise contamination that should benefit X-59 and future low-boom supersonic aircraft testing.

¹This chapter is derived from a peer-reviewed paper published in the Journal of the Acoustical Society of America with the following citation:

Anderson, M. C., Gee, K. L., Durrant, J. T., Loubeau, A., Doebler, W. J., Klos, J. (2024), "Reducing contaminating noise effects when calculating low-boom loudness levels," J. Acoust. Soc. Am. 155, 3889-3899 (2024) <https://doi.org/10.1121/10.0026436>.

© 2024 Acoustical Society of America. This material is reproduced here with permission. Minor changes have been made to fit within the context of this dissertation and to improve clarity and formatting. No conclusions or major results have been changed.

3.1 Introduction

Over the next several years, the National Aeronautics and Space Administration (NASA) will conduct supersonic aircraft flight tests for its Quesst Mission using the X-59 experimental aircraft. These tests will include sonic boom signature validation tests and, importantly, community noise tests (NASA, 2026; Ozoroski *et al.*, 2021; Rathsam, 2022). The X-59 will be flown over several communities to gather both acoustic and human annoyance data. This will provide an opportunity to estimate test participant annoyance on the ground to provide recommendations for legislation to enable future low-boom aircraft to fly over land (Loubeau and Page, 2018). To do so, NASA has chosen several metrics that correlate with human annoyance (Loubeau *et al.*, 2015; Loubeau and Page, 2018; Loubeau *et al.*, 2018). These metrics will be calculated for sonic booms (or “thumps”) produced by the X-59 to determine noise acceptability in communities. The six metrics are a modified version of the Stevens Mark VII Perceived Level of Loudness (PL), the Indoor Sonic Boom Annoyance Predictor (ISBAP), and the A, B, D, and E-weighted Sound Exposure Levels (ASEL, BSEL, DSEL, ESEL) (Stevens, 1972; Shepherd and Sullivan, 1991; Loubeau and Page, 2018).

Because the X-59 aircraft can produce booms with low sound levels on the ground, NASA and contractors tasked with gathering acoustic data are left with the question of how to handle low signal-to-noise ratio (SNR) measurement environments (Page *et al.*, 2014). As X-59 measurements will be deliberately made in urban environments, contaminating noise levels will be higher than in most previous test campaigns, which happened primarily in quiet ambient environments, with a few exceptions (Page *et al.*, 2014; Maglieri *et al.*, 2014; Page *et al.*, 2020; Gee *et al.*, 2020; Anderson *et al.*, 2022b). Although overall contaminating noise levels can be somewhat predicted using geospatial data and machine learning (Pedersen *et al.*, 2021; Doeblér, 2021), exact levels during a recording cannot, making it impossible to know the exact effects of contaminating noise on recordings ahead of time.

Klos (2020) and Klos (2022) show previous work on understanding contaminating noise effects and how to remove noise contamination in sonic boom metric calculations. Using the ISO 11204 standard as a framework (ISO 11204:2010, 2010), additional, more aggressive, corrections were developed. The best results were obtained by using the “Custom E” and “Custom F” corrections discussed in Klos (2022). These corrections successfully reduced the amount of noise contamination in metric calculations. Although this method appears to be largely successful, it is useful to investigate other methods that are also easily implemented. Using multiple methods can provide a way to validate the results.

Considering the amount of data that will be generated by X-59 testing, it is important to have a method for quickly and accurately removing noise contamination from recordings. The number of anticipated measurements for every boom is expected to be more than 100 because noise monitors will be spaced throughout the community and surrounding areas (Klos, 2020), and if a simple yet effective method for removing noise contamination can be implemented then overall effort and data analysis cost may be reduced.

The remainder of this chapter proceeds as follows. Section 3.2 contains the process and theory behind creating filters for removing contaminating noise. Section 3.3 discusses the required cutoff frequency for accurate metric calculations within ± 1 dB of a perfectly clean waveform when the

contaminating noise is perfectly defined. Section 3.4 then applies these filters to more realistic simulations. Following that, Sec. 3.5 includes a direct comparison between the Butterworth, Brick Wall, and ISO 11204 filters. Section 3.6 demonstrates that the Butterworth filter successfully removes statistical correlation between ambient and boom PL values in a real-world measured dataset, suggesting that the Butterworth filter can be useful for different-shaped booms. Overall, both the Butterworth and Brick Wall filters successfully reduce noise contamination, and therefore, reduce the total effective measurement cutoff frequency required for accurate metric calculations.

3.2 Filtering Techniques

This chapter presents two low-pass filters for high-frequency contaminating noise removal. The first is a time-domain zero-phase filter with sixth-order Butterworth filter magnitude response, hereafter referred to simply as the “Butterworth” filter. This filter is implemented via the MATLAB *butter* and *filtfilt* commands (The MathWorks, Inc., 2022). The *butter* command is used to generate a third-order filter, which is used as the input to the *filtfilt* command which applies the filter both forward and backward, producing zero phase distortion and doubling the final filter order to sixth order. The second filter presented in this chapter is a purely frequency-domain filter that is referred to as the “Brick Wall” filter. This filter simply discards all frequency data above a selected one-third octave (OTO) band and serves as a limiting case to help determine whether there are possible benefits of investigating other filter shapes.

To determine filter effectiveness on low-boom recordings, this chapter uses a dataset of simulated low-boom recordings from the X-59, which consists of predicted sonic boom ground signatures from a previous X-59 design iteration identified as “C609” (Rallabhandi and Loubeau, 2022). These simulations include propagation of the C609 near-field pressure through realistic atmospheric profiles without turbulence effects. The dataset is a random sample of the low booms produced in Doeblner *et al.* (2022). These waveforms have been resampled to a sample rate of 51.2 kHz and have been padded with zeros so that the peak pressure occurs at 0.1 seconds and the total waveform is 650 ms long. To simulate contaminating noise effects on these recordings, measured ambient recordings were used from the Quiet Supersonic Flights 2018 (QSF18) test campaign (Page *et al.*, 2020; Anderson *et al.*, 2022b), and superposed on the X-59 simulations. For this measurement campaign, data were recorded in Galveston, TX and the contaminating noise recordings are used here to simulate X-59 recordings in community environments. Because the analyses within this chapter are largely limited to simulated C609 waveforms with measured QSF18 ambient noise recordings, the results may not fully generalize to other waveform shapes and ambient noise environments. However, these methods are shown to work well on measured QSF18 sonic booms in Sec. 3.6, supporting the claim that these methods may be applicable to other sonic boom shapes.

The following discussion consists of a filtering analysis walk-through example. Figure 3.1(a) shows a C609 waveform both before and after contaminating noise from QSF18 is added. These waveforms are hereafter referred to as the “clean” and “noisy” waveforms, respectively. Spectra for the clean and noisy booms are shown in Fig. 3.1(b), alongside the spectrum for the contaminating noise. All results in this chapter use a 650-ms recording for both the contaminating noise and the

sonic boom. The spectra were calculated using a tapered cosine window with a cosine fraction of 0.1. Longer contaminating noise recordings could be used to estimate the contaminating noise spectrum if the ZSEL spectra for the boom and the noise are properly scaled to account for different recording durations. Because this is a simulation, the contaminating noise is perfectly known, and an independent spectrum can be produced. At low frequencies, the noisy recording is dominated by the sonic boom and at high frequencies is dominated by contaminating noise. An important metric for the noisy sonic boom is the frequency-dependent SNR, defined as

$$\text{SNR}(f) = \text{ZSEL}_{\text{boom}}(f) - \text{ZSEL}_{\text{ambient}}(f), \quad (3.1)$$

and plotted as a function of frequency in Fig. 3.1(c), where $\text{ZSEL}(f)$ is the flat-weighted sound exposure level spectrum. The key takeaways from this figure are that the highest SNR values occur around or below 10 Hz for this recording and that contaminating noise completely overwhelms the recording at frequencies greater than about 600 Hz. Because most of the metrics are impacted more by frequencies in the hundreds of Hertz range than in the tens of Hertz range, this chapter focuses on removing the high-frequency noise. This work could potentially be combined with the wind noise removal techniques found in Cook *et al.* (2021) to reduce any contamination due to wind noise at low frequencies. Results in this chapter indicate that focusing only on high frequencies performs remarkably well.

The process for implementing the filter is as follows:

1. Calculate the SNR spectrum using Eq. (3.1) as shown in Fig. 3.1(c).
2. Determine the first OTO band center frequency with an SNR below a chosen threshold. This frequency becomes known as the “cutoff frequency”. This chapter uses a threshold of 3 dB.
3. Set that OTO band center frequency to be the filter cutoff frequency.
4. Apply the filter to the waveform (Butterworth) or spectrum (Brick Wall). The resultant spectra are shown in Fig. 3.2. For the Brick Wall filter, simply discard all OTO band spectral data above this cutoff frequency, keeping the value at the cutoff frequency itself. For example, if the SNR drops below 3 dB between 250 and 315 Hz, the cutoff frequency is 250 Hz. Spectral data corresponding to 315 Hz and above are discarded, while data at 250 Hz and below are kept.

Note that other filter designs and filter orders may yield acceptable or even better results. An exhaustive search of filters and orders was not performed, and the Brick Wall filter results throughout the remainder of this chapter demonstrate that precisely matching the spectral shape is not important for accurate metric calculations.

Note also that many booms suffer from low-frequency contamination that tends to be at frequencies unimportant to most metrics but may cause the filter to be applied at an unnecessarily-low frequency. To avoid this, all results in this chapter use a minimum allowable cutoff frequency of 50 Hz, and if the low-SNR threshold was crossed before 50 Hz, then the cutoff frequency was set to

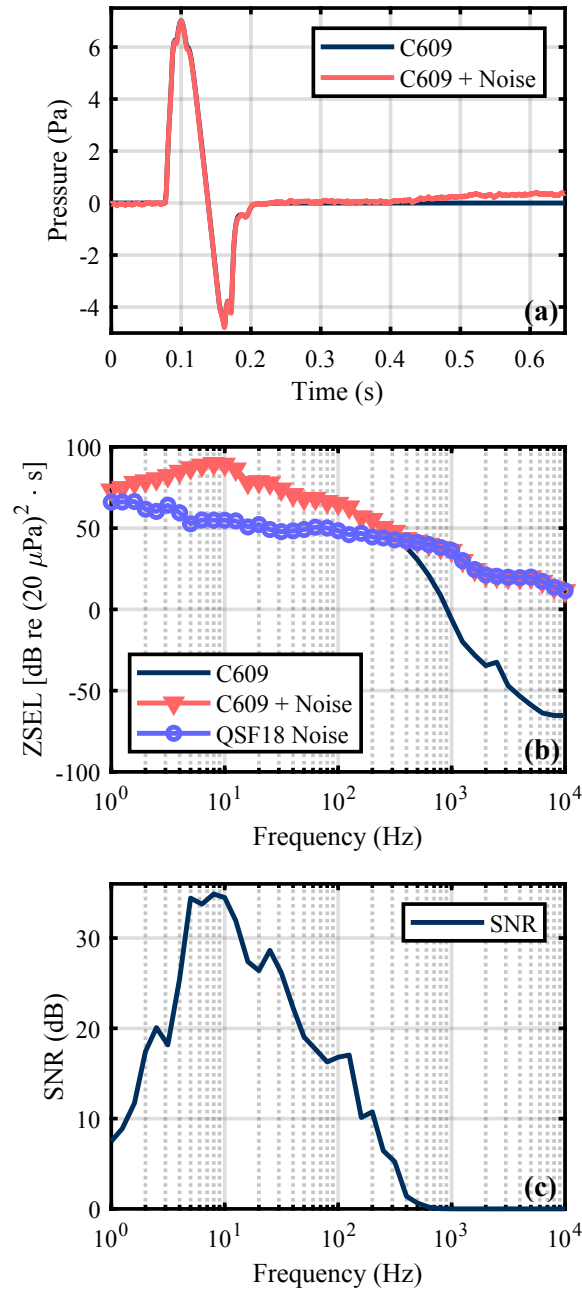


Figure 3.1 (a) An example simulated C609 waveform with and without added contaminating noise. (b) The OTO band spectra for the waveforms. Also included is the contaminating noise that was added to the clean boom to produce the noisy boom. (c) The signal-to-noise ratio spectrum for the noisy boom (C609 + Noise) relative to the contaminating noise (QSF18 Noise).

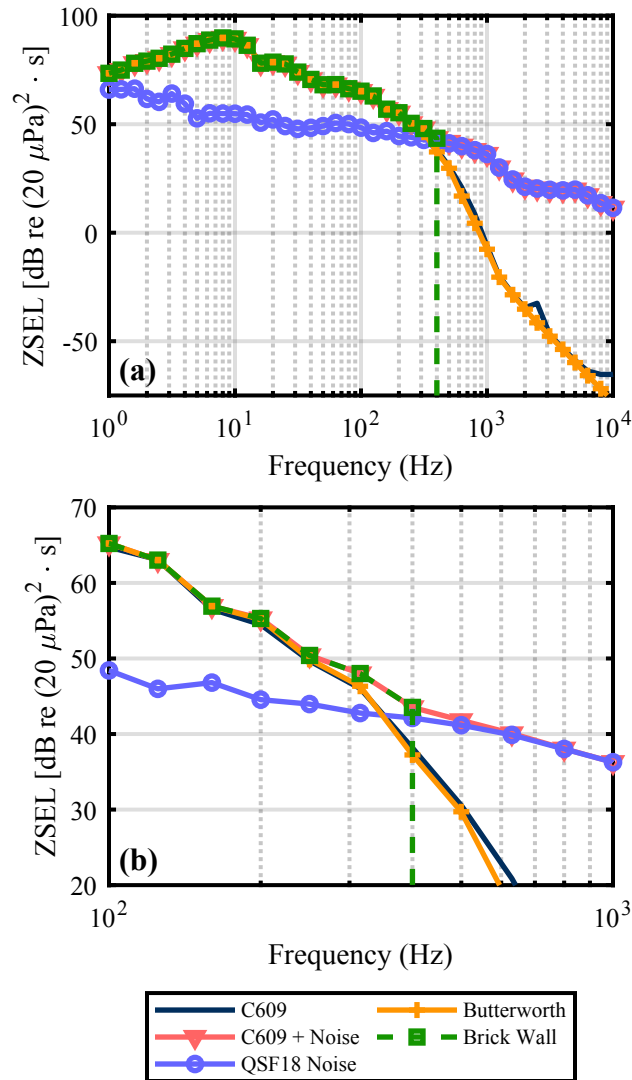


Figure 3.2 The combined spectra. Notice that for this boom the Butterworth filter follows the high-frequency rolloff closely. (a) The full spectra. (b) The zoomed-in spectra. Notice that the Brick Wall filter keeps the value associated with the cutoff frequency of 400 Hz, removing all data above the cutoff frequency but not at the cutoff frequency itself.

the first frequency greater than 50 Hz for which the SNR threshold was crossed. The work of Cook *et al.* (2021) may be useful in the future to remove this constraint.

Another important set of visualizations when calculating sonic boom metrics are the loudness curves produced during the PL calculation. These curves are shown in Fig. 3.3 both with and without the filtered spectra. In Fig. 3.3(a), we see that the frequencies for which these sonic booms have their peak SNR (as shown previously in Fig. 3.1(c)) are not the frequencies that contribute most to loudness, but rather the frequencies around 100 Hz. This is important because it means that the frequencies that are the most impactful for calculating the PL have lower SNR values, increasing the likelihood of metric inflation due to contaminating noise. In Fig. 3.3(b), we see the same loudness curves, but with the two filtered results overlaid, showing how both filters reduce noise contamination at high frequencies. It is important to note that the standard PL calculation for sonic booms uses a correction designed specifically for sonic booms that accounts for two shocks in the waveform (Shepherd and Sullivan, 1991). Although it is currently standard practice to use this same correction when calculating the PL for a sonic boom and its surrounding contaminating noise (Page *et al.*, 2014), its appropriateness for contaminating noise levels is not well-understood. To stay consistent with the literature (Page *et al.*, 2014, 2020), this chapter uses the current standard practice of applying this correction to the boom and ambient PL metrics; however, the correction's applicability to contaminating noise and sonic booms that do not match the assumptions made in Shepherd and Sullivan (1991) warrants future analysis.

Once the lowpass filter has been applied, we can compare the metric values for the clean, noisy, and filtered C609 simulations. Table 3.1 shows these results for the example boom discussed in Figs. 3.1–3.3. Notice that the noisy boom tends to have inflated metric values due to the addition of contaminating noise, especially for the PL, ISBAP, and ASEL. Both filters reduce the contaminating noise impact and show good agreement with the clean metric values. Also, both filters produce the same final metric values within 0.2 dB. This demonstrates that both filters are approximately equally effective for this boom. Note also that several metrics are essentially unaffected by the contaminating noise.

3.3 Results with Known Contaminating Noise

The same analysis described above was applied to a set of 300 similar simulations using the C609 simulations and real-world contaminating noise. Each boom was randomly paired with ambient data recorded at QSF18 and was analyzed 30 times with different contaminating noise recordings drawn from a bank of 5,081 potential 650-ms recordings. Because contaminating noise recordings were randomly selected, there were a few repeated combinations. The duplicates were removed, and, in the end, there were 8,973 unique pairings of boom and ambient recordings. Analyses were performed exactly as discussed above, with the contaminating noise being perfectly known for each recording. Section 3.4 discusses applications to simulated data where the contaminating noise is not perfectly defined.

Two metrics are shown in detail here: PL and BSEL. The results for both metrics are shown in Fig. 3.4. In each subplot, all booms are represented exactly once as a function of their individual

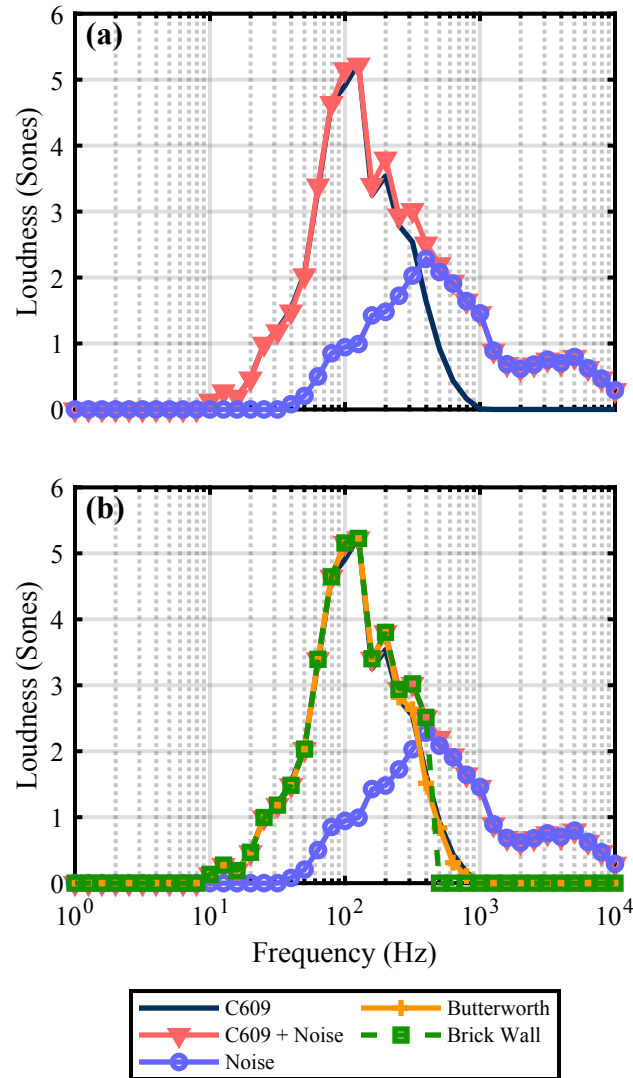


Figure 3.3 (a) Loudness spectra for the original C609 recording, the C609 recording with contaminating noise, and the contaminating noise on its own. (b) The same loudness spectra as (a), but the loudness spectra of the C609 recording with contaminating noise has been filtered according to the Butterworth and Brick Wall methods and shown.

Table 3.1 The metric calculations for the simulated C609 walk-through example shown in this section. Notice that both the Butterworth and Brick Wall filters can reduce the noise contamination to better-approximate the metrics from the clean recording. Although not considered part of the candidate metrics for sonic booms, CSEL and ZSEL are included for completeness. All values are shown in decibels.

	Clean Value	Noisy Value		Butterworth Filter Result		Brick Wall Filter Result	
		Result	Difference	Result	Difference	Result	Difference
PL	66.6	69.6	3.0	66.6	0.0	66.7	0.1
ISBAP	78.9	81.5	2.6	78.9	0.0	78.9	0.0
ASEL	53.1	54.0	0.9	53.3	0.2	53.5	0.4
BSEL	68.0	68.1	0.1	68.1	0.1	68.1	0.1
CSEL	82.4	82.4	0.0	82.4	0.0	82.4	0.0
DSEL	70.6	70.7	0.1	70.6	0.0	70.6	0.0
ESEL	63.4	63.7	0.3	63.6	0.2	63.6	0.2
ZSEL	96.7	96.6	-0.1	96.6	-0.1	96.6	-0.1

cutoff frequency on the abscissa. The ordinate contains the change in metric value relative to the clean, no-noise-added boom. The following labels are useful for this figure and throughout the following discussions.

$$\Delta PL_{n-c} = \text{noisy PL} - \text{clean PL} \quad (3.2)$$

$$\Delta PL_{f-c} = \text{filtered PL} - \text{clean PL} \quad (3.3)$$

$$\Delta PL_{n-f} = \text{noisy PL} - \text{filtered PL} \quad (3.4)$$

In subplot (a), the difference created by applying the contaminating noise to the clean boom is shown. For example, if the clean PL of the simulated boom is 75 dB, but adding noise creates a PL of 78 dB and reduces the boom cutoff frequency to 400 Hz, then a single dot is placed on this subplot at (400 Hz, 3 dB). The process is repeated for all boom and noise realizations. The result is 8,973 data points segregated by cutoff frequency. Therefore, a distribution of ΔPL values exists at each frequency band and some statistical results are shown on the plot at each band. The green bars denote plus and minus two standard deviations from the mean value of the distribution and the blue bars denote the 95% confidence interval for the mean value of the distribution. These statistics help to visualize the spread and number of data points at each frequency. Subplot (b) shows the same type of plot for the BSEL metric. Notice that the BSEL is substantially less affected by contaminating ambient or instrumentation noise than the PL. Subplot (c) shows the PL results again, but after applying the Butterworth filter to the noisy booms. Notice that after applying this filter, the mean values tend to lie much closer to 0 dB and the standard deviation bars have become smaller. This indicates that, although there is still spread in the data, the mean PL values calculated after

applying the Butterworth filter are much closer to the benchmarks. Subplot (d) shows the same for BSEL and subplots (e) and (f) represent the same results using the Brick Wall filter instead.

From Fig. 3.4, the required cutoff frequency for accurate metric calculations can be estimated. The estimate is obtained by determining the required cutoff frequency for the mean plus or minus two standard deviations to lie within ± 1 dB of the corresponding metric for the clean boom. Graphically, this is the required cutoff frequency such that the green bars do not stray beyond ± 1 dB, and this analysis can be performed for the unfiltered case as well as the two filtered cases. This produces the results shown in Table 3.2, and a few of the results can be compared visually with Fig. 3.4. Each row indicates results for a given metric, shown in the left-most column. Results were truncated at 50 Hz because that was the minimum allowed cutoff frequency. A primary result from this table is that both the Butterworth and Brick Wall filters successfully reduced the cutoff frequency required for good metric agreement with the clean booms. Another important result is that there is little difference between the required cutoff frequencies for the two types of filters. The choice of ± 1 dB is arbitrary and other criteria could certainly be chosen. It should be noted that although nearly 10,000 realizations were used, the cutoff frequency values listed in Tables 3.2 and 3.3 may change a little depending on the simulation details. Such appears to be the case for the ZSEL metric, which shifts from 160 Hz in Table 3.2 across all three columns to 125 Hz in Table 3.3 (in Sec. 3.4) across all three columns, a change of a single OTO band. Despite this small change that can occur for the recommended cutoff frequencies, the trends remain intact, and the cutoff frequencies do not vary dramatically between simulations.

The fact that the ZSEL metric requires a higher cutoff frequency than the CSEL metric can be explained by the presence of low-frequency noise sources like wind noise, which corrupt the ZSEL metric more than the CSEL metric. Thus, for applications where the ZSEL is important, low-frequency noise reduction should be considered. For wind noise reduction, the work in Cook *et al.* (2021) may be useful. As both the CSEL and ZSEL metrics are not in the list of NASA human-perception metrics (Loubeau and Page, 2018), having been included within this chapter for completeness only, these interesting results may not be a primary concern for the upcoming X-59 community flight tests.

These results indicate that both the Butterworth and Brick Wall filters can be used for accurate sonic boom metric calculations using the current metrics and when high-frequency noise is the dominant contaminating noise source.

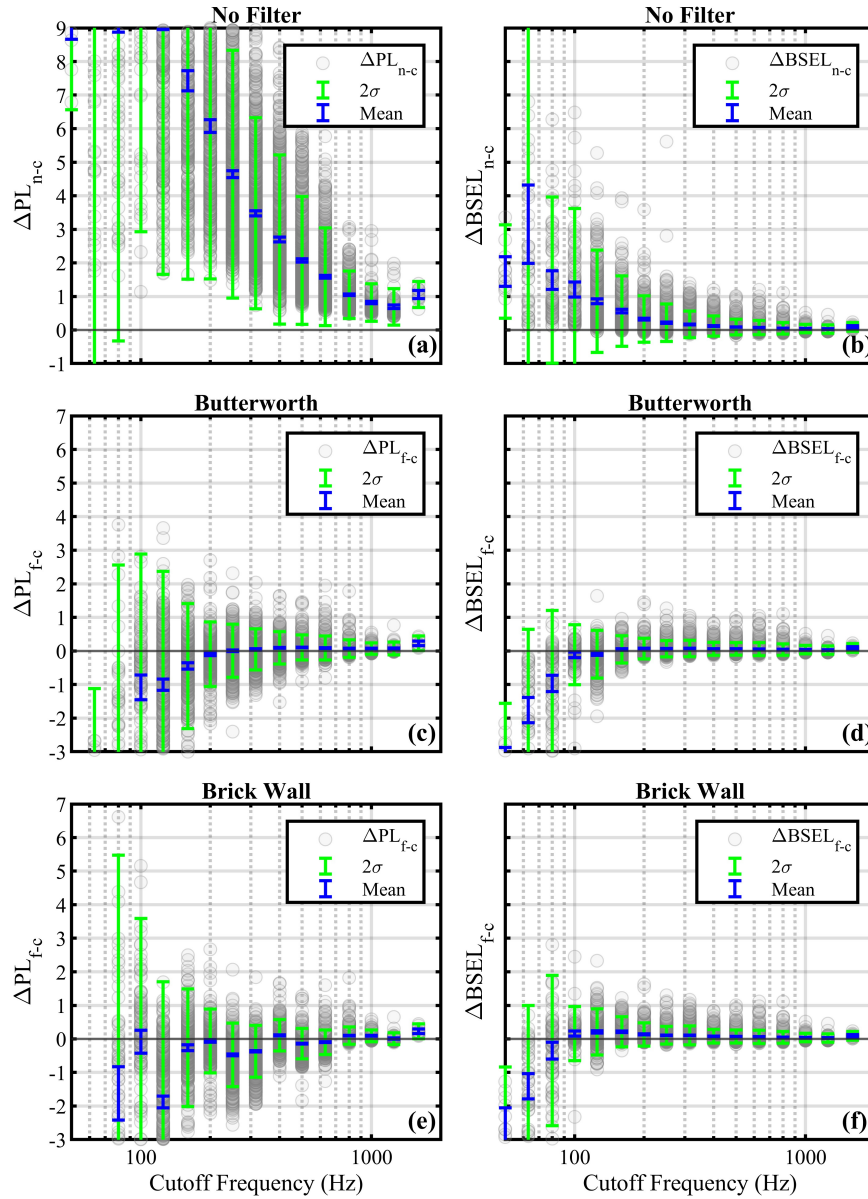


Figure 3.4 The difference, relative to the clean boom, as a function of the cutoff frequency. (a) The unfiltered PL value (dB) minus the clean boom PL (dB). The difference is denoted by ΔPL_{n-c} where the quantity “n-c” denotes “noisy minus clean.” The circles represent individual boom realizations, so there are a total of 8,973 circles on this plot. Green bars denote two standard deviations for the distribution at each frequency. Blue bars denote the 95% confidence interval for the mean value of the distribution at each frequency. (b) Same, but for the BSEL metric. (c) The same results for PL, but after applying the Butterworth filter. The quantity ΔPL_{f-c} denotes “filtered minus clean.” (d) Same, but for the BSEL metric. (e) Same, but for the PL metric using the Brick Wall filtering technique. (f) Same, but for the BSEL metric.

Table 3.2 The results of using different filtering techniques on the minimum cutoff frequency required for accurate metric calculations within 1 dB, defined as the mean $\pm$ two standard deviations. These results are for the case that the contaminating noise is perfectly known. Frequencies are the OTO band center frequencies.

	Unfiltered (Hz)	Butterworth Filter (Hz)	Brick Wall Filter (Hz)
PL	>1600	250	400
ISBAP	>1600	200	400
ASEL	800	200	250
BSEL	250	125	100
CSEL	50	50	50
DSEL	200	100	80
ESEL	500	160	160
ZSEL	160	160	160

3.4 Filter Applicability to More-Realistic Simulations

3.4.1 Contaminating Noise Stationarity

If the contaminating noise is not stationary over short intervals, then attempting to remove contaminating noise becomes more challenging. It is therefore relevant to consider the question of how stationary the contaminating noise is over short intervals. To investigate this, 2,383 contaminating noise recordings from QSF18 of duration 1300 ms were used to determine spectral differences between the first and second halves of the recordings. These recordings were created using the channels with the lowest instrumentation noise at the four stations that recorded about one minute of ambient noise before each sonic boom measurement. These four stations are discussed further in Anderson *et al.* (2022b). Results are shown in Fig. 3.5. At frequencies below about 20 Hz, there is much more variability between recording halves, perhaps due to wind noise. However, the high SNR during most sonic boom recordings at those frequencies means that this is unlikely to substantially impact metric calculations.

3.4.2 Mock Recordings

Table 3.2 described the necessary cutoff frequency for accurate metric calculations when contaminating noise during the boom recording is perfectly known. To better simulate a real-world recording where contaminating noise is known only before the boom (i.e., “preboom ambient”), a 1300-ms recording of contaminating noise is added to each 650-ms boom with the boom in the second half of the recording. An example of this is shown in Fig. 3.6. Therefore, only the 650 ms of contaminating noise immediately preceding the boom is known, and the 650 ms of contaminating noise during the boom can only be estimated, which is more typical of real-world measurements (Page *et al.*, 2014). These types of waveforms are referred to hereafter in this chapter as “mock recordings.”

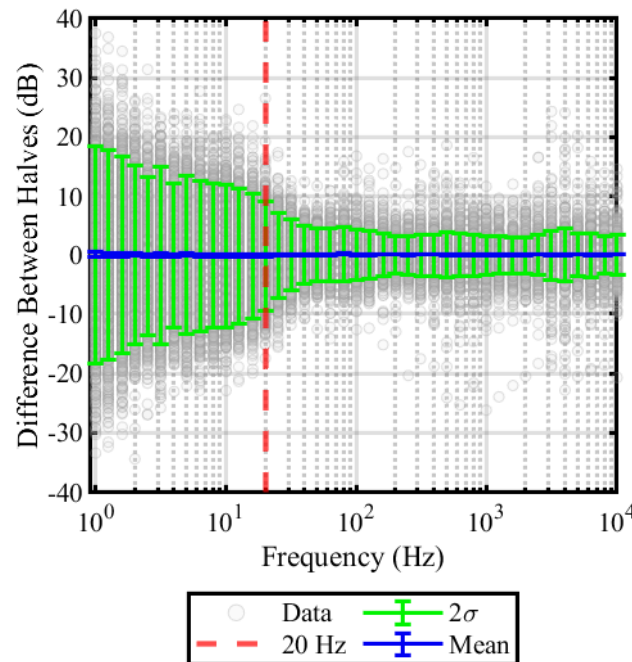


Figure 3.5 Analysis of contaminating noise variability at QSF18. Levels at frequencies below about 20 Hz can change much more than levels at higher frequencies over the course of 1300 ms.

To simulate a real-world measurement, 8,956 unique mock recordings were created by randomly pairing the 300 C609 booms with 1300-ms segments from contaminating noise recordings from four stations at QSF18 (Page *et al.*, 2020; Anderson *et al.*, 2022b). Contaminating noise before the boom was used to estimate the SNR during the boom, and the filters were applied. Results are shown in Table 3.3. Several metrics show that a higher cutoff frequency is required for accurate metric estimations relative to the case where contaminating noise is perfectly-known (Table 3.2), following from the increased uncertainty in contaminating noise levels during the recording. This is further illustrated in Fig. 3.7, which shows the same type of results as Fig. 3.4, but using these mock recordings, where the noise during the sonic boom is not perfectly known, only estimated. Notice the increase in the uncertainty when the contaminating noise is not perfectly known. Experience shows that the recommendations in Table 3.3 may drift by a couple bands between different simulations, though the trends remain intact.

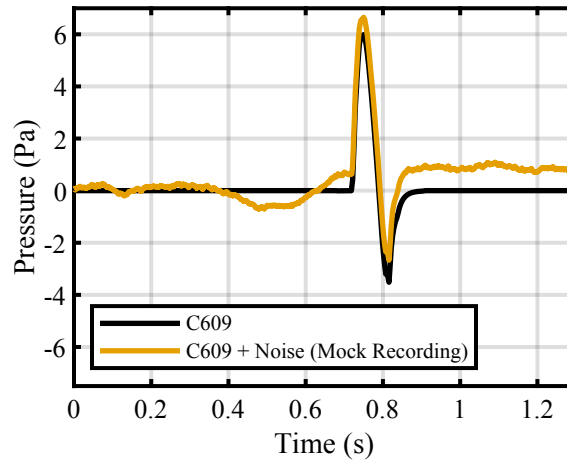


Figure 3.6 An example mock recording. A 1300-ms contaminating noise recording is combined with the clean boom. This results in 650 ms of contaminating noise before the boom window, allowing for analyses to be performed that use the first 650 ms of contaminating noise to estimate contaminating noise during the actual boom event. This is more realistic because the contaminating noise during the boom is not able to be perfectly known.

Table 3.3 Results of using different filtering techniques on the minimum cutoff frequency required for accurate metric calculations (mean $\pm$ 2 standard deviations) within 1 dB. These results are for the case that the contaminating noise is not perfectly known but is estimated by using the 650 ms before the boom.

	Unfiltered (Hz)	Butterworth Filter (Hz)	Brick Wall Filter (Hz)
PL	>1600	400	400
ISBAP	>1600	400	400
ASEL	1000	400	400
BSEL	200	125	100
CSEL	50	50	50
DSEL	160	100	80
ESEL	500	160	200
ZSEL	125	125	125

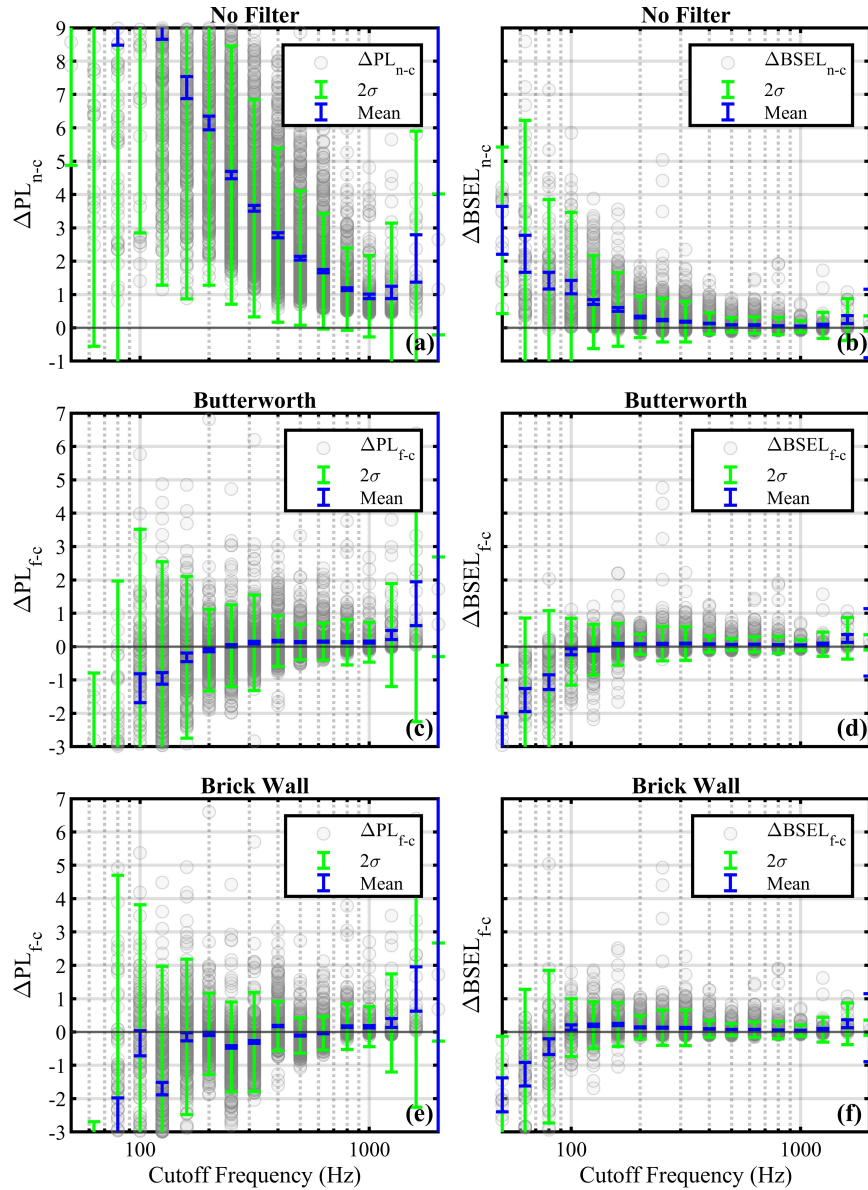


Figure 3.7 The difference, relative to the clean boom, as a function of the cutoff frequency. (a) The unfiltered PL value (dB) minus the clean boom PL (dB). The difference is denoted by ΔPL_{n-c} where the quantity “n-c” denotes “noisy minus clean.” The circles represent individual boom realizations, so there are a total of 8,956 circles on this plot. Green bars denote two standard deviations for the distribution at each frequency. Blue bars denote the 95% confidence interval for the mean value of the distribution at each frequency. (b) Same, but for the BSEL metric. (c) The same results for PL, but after applying the Butterworth filter. The quantity ΔPL_{f-c} denotes “filtered minus clean.” (d) Same, but for the BSEL metric. (e) Same, but for the PL metric using the Brick Wall filtering technique. (f) Same, but for the BSEL metric.

3.5 Comparison with ISO 11204

How does this filtering technique compare with other state-of-the art techniques? A popular technique for reducing contaminating noise corruption is to use a spectral subtraction method (Page *et al.*, 2014; Klos, 2022), such as that used in ISO 11204 (ISO11204:2010, 2010). A spectral subtraction method takes the preboom ambient and boom spectra and subtracts them on an energy basis before calculating metrics. A revised, more aggressive, formulation of ISO 11204 can be found in Klos (2022), and the revised filters recommended in that work are the “Custom E” and “Custom F” corrections. The Brick Wall and Butterworth filters proposed in this chapter are directly compared against these two modified ISO 11204 corrections, where the same 8,956 mock recordings were used from Sec. 3.4. The differences between the filtered mock recording and the clean boom PL values (ΔPL_{f-c}) were calculated and are shown in Fig. 3.8 and a few statistics for the distributions are shown in Table 3.4. Subplot (a) shows only the results using the ISO 11204 adaptations. Subplot (b) superimposes the results from the methods proposed in this chapter.

Notice that all four methods produce similar results, with the methods produced in this chapter perhaps slightly outperforming the ISO 11204-based methods by producing more values near $\Delta PL_{f-c} = 0$ dB. However, based on this analysis alone, none of these methods stand out as a clear choice. It is possible that additional simulations and measurements will determine the best approach to contaminating noise mitigation. These methods should all continue to be studied once real low-boom measurements are available, and we should be careful not to draw final conclusions based on simulated results that may work great for particular simulations but not fully generalize to other sonic booms and ambient noise environments. It is possible that during X-59 testing, multiple methods should be used in tandem to help estimate uncertainty in the final metric values. It is likely that the ISO 11204-based methods will outperform the methods presented in this chapter when the contaminating noise is tonal. However, because the Butterworth filter is a time-domain technique, it could possibly be used to produce waveforms with reduced high-frequency noise contamination.

Table 3.4 Statistical descriptions of the distributions shown in Fig. 3.8.

	Mean (dB)	Standard Deviation (dB)
No Filter	3.5	3.1
ISO 11204 (E)	-0.3	1.1
ISO 11204 (F)	0.6	1.4
Butterworth	-0.1	1.4
Brick Wall	-0.3	1.4

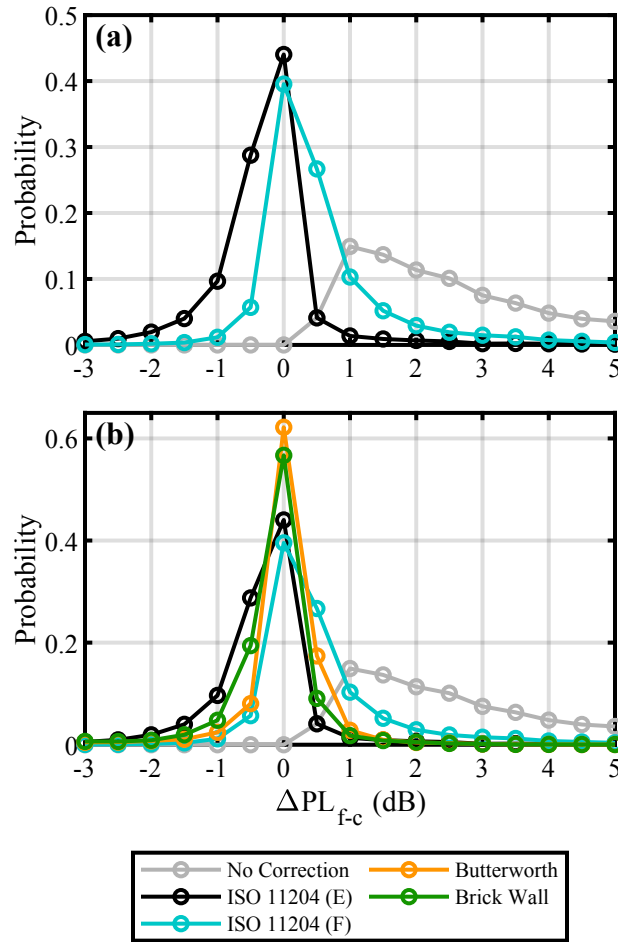


Figure 3.8 Comparison with the ISO 11204-based methods. (a) The distribution of filtered metrics relative to the clean boom. (b) Same distributions, but with the methods proposed in this chapter included.

3.6 Reducing Statistical Correlation Between Signal and Contaminating Noise

An important consideration for this work is whether the methods presented in this chapter are useful for real-world measurements and waveforms that do not have the same shape as the C609 simulations. Because real-world measurements do not have known “clean” metric values, determining whether a method successfully removes the contaminating noise cannot be demonstrated exactly. However, it can be investigated statistically. A linear fit can be created for the data both before and after contaminating noise removal, returning an estimated slope and a p-value associated with that slope. Figure 3.9 shows the result of such an analysis on the QSF18 dataset. This dataset consists of sonic booms produced by an F-18 aircraft performing a low-boom dive maneuver about 20 miles off the

coast of Galveston, TX (Page *et al.*, 2020; Anderson *et al.*, 2022b). In total, 379 boom PL values from QSF18 are plotted as a function of the corresponding ambient PL. Sonic booms with a cutoff frequency less than or equal to 50 Hz were omitted, as those are likely too contaminated to acquire accurate metric calculations. Figure 3.9(a) shows the unfiltered boom results. There is a clear trend for the boom PL to be greater if the ambient PL is also greater. The red line indicates the fitted linear model. Note that the p-value is 2.71×10^{-9} , indicating a strong statistical relationship between the ambient and boom PL values (i.e., a strong likelihood of a nonzero fitted slope). The almost perfectly straight lower boundary in the scattered data results from the boom PL being limited to the ambient PL, creating an effective floor for the PL metric. This is visualized by adding the blue line, which represents a one-to-one relationship between the ambient and measured boom levels. Figure 3.9(b) shows the same data, but where the boom PL values have been replaced by their corresponding values after applying the Butterworth filter. Note that the effective floor is gone and that the p-value has increased many orders of magnitude to 0.322, demonstrating that there is a substantially weaker statistical relationship between ambient and boom PL values (i.e., the fitted slope is much more likely to be equal to zero). Most importantly, the metric values are no longer bounded by the noise measured prior to the boom. Although the range of PL values is much larger after the filtering has been applied, many of these low PL values are associated with sonic booms waveforms with longer rise times and hence less high-frequency energy. It is not entirely surprising that these sonic booms should have low PL values. However, whether these particularly-low metric values truly correspond to human perception remains an open question. It is possible that an end user would choose to simply discard any measurements below a pre-determined threshold.

3.7 Conclusion

This chapter discusses the importance of removing noise contamination in low-boom measurements. The required cutoff frequency for accurate metric calculations is dramatically decreased by applying either a Brick Wall or a sixth-order Butterworth-magnitude filter to the recordings above the frequency at which the SNR drops below 3 dB. Results vary across metrics, but all shown metrics require a cutoff frequency of only 400 Hz or less for accurate calculations within ± 1 dB. If no filter is applied, some metrics require a cutoff frequency many times higher, some of which may not even be practically possible in the field.

The Brick Wall and Butterworth filters are successful and robust. Both filters are shown to produce metric calculations that are at least as accurate as the ISO 11204-based method for the test cases shown, even with the Custom E and Custom F corrections (Klos, 2022). However, for other use cases beyond sonic booms, such as when there is tonal noise or an inconsistent high-frequency rolloff, the ISO 11204 standard may produce better results because it performs a band-by-band correction. In future endeavors, it may be possible to use the Butterworth filter to produce waveforms with reduced high-frequency contaminating noise. All the methods assume stationarity in the contaminating noise, and accuracy will be lost when that assumption is not met.

The two proposed filters, the Brick Wall and Butterworth filters, are straightforward and simple to implement. All the user needs to do is record a short amount of contaminating noise before each

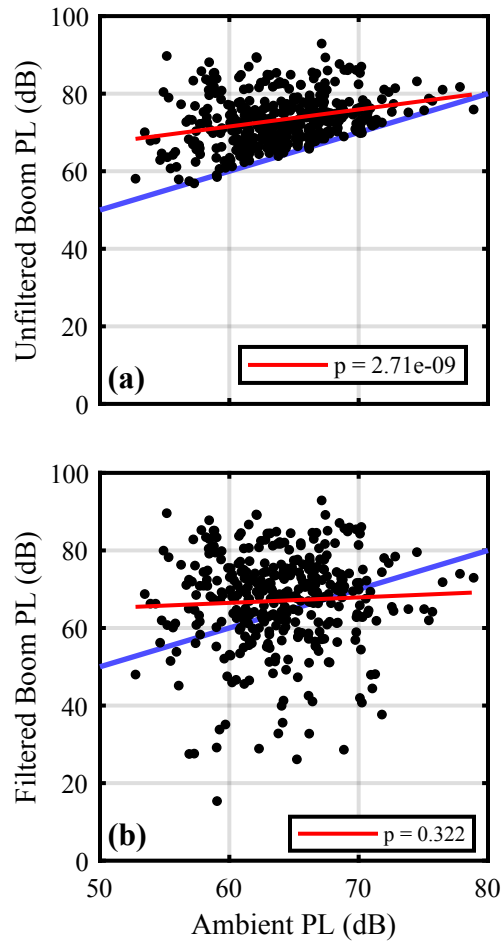


Figure 3.9 Results of applying the Butterworth filter to the QSF18 dataset. Boom PL is shown as a function of ambient PL, using the 650-ms window immediately before the 650-ms window containing the boom. A total of 379 booms were used: (a) without filtering and (b) after applying the Butterworth filter. The red line indicates the linear fit between the boom and ambient levels and the blue line indicates a one-to-one relationship between levels.

boom, calculate the SNR spectrum, and set the filter cutoff frequency to be at the point where the SNR drops below a chosen threshold. Additionally, the Butterworth filter removes the statistical relationship between ambient PL values and sonic boom PL values for measured QSF18 data, indicating that at least the Butterworth method can likely be applied to sonic booms with different shapes than the C609 simulations. The Brick Wall filter's overall success indicates that attempting to perfectly match the high-frequency rolloff of sonic boom spectra is unlikely to yield major improvements. These and other methods should be investigated further when measured low-boom data become available.

Acknowledgements

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Chapter 4

Comparing Measured Turbulence-induced Variability with Simulated Statistics

Abstract

¹When a sonic boom signature passes through the atmospheric boundary layer, it becomes distorted. These distortions are random and change over short distances. The NASA Sonic Booms in Atmospheric Turbulence (SonicBAT) effort, which concluded in 2018, focused on developing modeling tools for these turbulence effects on signatures from supersonic aircraft overflight. In 2019, Brigham Young University participated in a NASA supersonic flight test campaign known as Carpet Determination in Entirety Measurements I (CarpetDIEM I). A 120-meter (400-foot) linear turbulence array with seven microphones was placed within the sonic boom carpet to assess turbulence effects on waveforms, spectra, and metric values. State-of-the-art modeling tools (PCBoom and KZKFourier) are combined with two weather models (CFSv2 and ERA5) to model metric variability for comparison with the measurements. The success rates are between 25% and 70%, depending on the metric and the confidence limits. As these predictions do not use any measured turbulence data, it is strongly recommended that future test campaigns acquire simultaneous turbulence data to improve the prediction accuracy beyond what can be achieved with simulation alone. A method for placing uncertainty estimates on metric standard deviation values is implemented and recommended for future practice.

¹This chapter is derived from a paper that has been submitted to a peer-reviewed journal, with the following approximate citation:

Anderson, M. C., Doeblner, W. J., Gee, K. L., Nyborg, K., Loubeau, A. (Submitted 2026). “Comparing measured sonic boom turbulence-induced variability with computational models for the Carpet Determination in Entirety Measurements (CarpetDIEM) I test campaign.”

The material presented here is the author’s own work, in collaboration with the coauthors listed above, and is included as part of this dissertation. Minor changes have been made to fit within the context of this dissertation and to improve clarity and formatting. No conclusions or major results have been changed.

4.1 Introduction

Turbulence-induced variability has long been known to affect sonic boom signatures (Hilton *et al.*, 1964; Hubbard *et al.*, 1964; Hilton *et al.*, 1966). These variations generally include either sharpened or rounded peaks, though a variety of waveform shapes can be measured (Lipkens and Blackstock, 1998; Maglieri and Sothcott, 1990). Because these changes tend to affect the higher frequencies contained within the sonic boom signature, the various human perception metrics can be strongly affected by these variations (Stout, 2018; Bradley *et al.*, 2020; Durrant *et al.*, 2022b). As these metrics are anticipated to be used in the near future to determine criteria for permissible noise levels from supersonic overflight (Loubeau *et al.*, 2015; Loubeau and Page, 2018) the effects due to turbulence are critical for determining the variability in final measurements. The purpose of this chapter is to provide measured results from a field test campaign and assess the accuracy of state-of-the-art tools in predicting the variability.

Recent NASA supersonic flight test campaigns have either noted or directly studied turbulence-induced variability (Bradley *et al.*, 2020; Durrant *et al.*, 2022b; Page *et al.*, 2015; Doebler, 2017). The foremost among these campaigns is the Sonic Booms in Atmospheric Turbulence (SonicBAT) campaign, which studied the effects of turbulence in both dry and humid environments along with simultaneous atmospheric turbulence measurements. A primary purpose of the SonicBAT campaign was to develop and validate computational tools for statistically predicting turbulence effects (Stout, 2018; Bradley *et al.*, 2020). The KZKFourier turbulence model was developed during SonicBAT and is described in detail in Stout (2018).

Another recent flight test is the Superboom Caustic Analysis and Measurement Program (SCAMP) (Page *et al.*, 2015). Although turbulence measurements were not the primary goal, Doebler (2017) analyzed turbulence effects using a subset of the SCAMP dataset that had straight, constant Mach number, passes over the 3-km (10,000-ft) linear microphone array. That analysis estimates the number of microphone measurements required to achieve reasonably converged confidence interval widths on perception metrics for a supersonic aircraft flyover. The final recommended number of microphones by Doebler (2017) is between 7–10 measurements separated by about 30 m (100 ft) for a microphone array that is both effective and practical in size.

Although simulations predict that turbulence-induced variability will have a smaller impact on shaped booms (Stout and Sparrow, 2018; Carr *et al.*, 2022; Stout and Sparrow, 2022), the overall trends between N-waves and shaped booms are similar, and there remain outliers in both cases (Stout, 2018). Thus, it is relevant to study turbulence-induced variability for N-waves because the results imply trends for shaped booms.

The purpose of this chapter is to take acoustic measurements from a recent sonic boom test campaign and compare the measured turbulence-induced variability to predictions using PCBoom (a common acoustic propagation tool for sonic booms; (Lonzaga *et al.*, 2022)), KZKFourier, and modeled turbulence parameters from two different atmospheric models. The atmospheric models are the Climate Forecast System Version 2 (CFSv2) (Saha *et al.*, 2014) and the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5 (ERA5) (Hersbach *et al.*, 2020). The modeled results are compared to the measured results to assess modeling accuracy. It is important to highlight that the predictions use only simulated results, with the exceptions of as-flown trajectories

and measured stratified atmosphere data for ray tracing to the top of the atmospheric boundary layer, and thus demonstrate the combined effectiveness of current modeling tools. The test campaign from which acoustic data are obtained is the Carpet Determination in Entirety Measurements I (CarpetDIEM I) test campaign performed in July-August 2019 (Durrant *et al.*, 2022b).

This chapter proceeds as follows. The measurements are discussed in Sec. 4.2. Section 4.3 then includes a discussion of turbulence during CarpetDIEM I with data from two different atmospheric models. In Sec. 4.4, the subject of placing uncertainty bounds on perception metric standard deviation estimates is discussed. Section 4.5 contains an analysis of the measured metric variability during the CarpetDIEM I test campaign. Lastly, Sec. 4.6 contains a comparison of the measured data against simulated results using a combination of PCBoom, KZKFourier, and data from both atmospheric models.

4.2 Measurements

The NASA CarpetDIEM I test campaign occurred in July-August 2019 (Durrant *et al.*, 2022b) with the primary goal of testing logistics for future X-59 flights that will occur in the same desert area near Edwards Air Force Base (EAFB) and NASA Armstrong Flight Research Center (AFRC). Sonic booms were produced by an F/A-18A aircraft flying at about Mach 1.3 at an altitude of about 9.1 km (30,000 ft). Over three flight days, there were 6 flights, resulting in 23 total passes over a ground microphone array.

At one of the ground measurement stations, located directly undertrack and nearly orthogonal to the anticipated carpet centerline, BYU deployed a small linear array of seven microphones spaced over 120 m (400 ft) to study the effects of atmospheric turbulence on the sonic booms, as shown in Fig. 4.1 (Durrant *et al.*, 2022b; Anderson *et al.*, 2024a). Because the array size is small compared with the aircraft altitude, it is assumed that atmospheric turbulence effects are the primary contributor to variability across the array and that any off-center flight effects are negligible. The shortest spacing was 15 m (50 ft), consistent with the conclusions of Roberts *et al.* (1967) and reiterated by Maglieri *et al.* (2014) that the measurements must be at least 7.6-15 m (25-50 ft) apart to observe turbulence-induced changes. Due to hardware constraints, two types of ½-inch microphones were used at this location: three PCB 378A07 microphones and four GRAS 40AE microphones. Each microphone was placed inverted over a circular plastic ground plate and shrouded in a domed windscreen (Anderson *et al.*, 2022a; James *et al.*, 2020a). The GRAS 40AE microphones have a low-frequency cutoff that does not allow accurate representation of the linear ramp portions of the waveform, i.e., between the shocks. This was corrected for in all measurements via digital pole-shift filtering (Rasband *et al.*, 2023; Marston, 2008; Anderson *et al.*, 2024c). Additionally, high-frequency contaminating noise was removed from the metric calculations using the methods in Anderson *et al.* (2024b).

Additionally, owing to the higher sensitivity of the GRAS 40AE microphones, some measurements experienced peak-pressure clipping. When deemed sufficiently minor to not impact metric calculations (see Chapter Appendix 4.8), they were used for further analysis alongside the unclipped measurements. If the clipping was deemed sufficient to affect calculations of Perceived Level (PL)

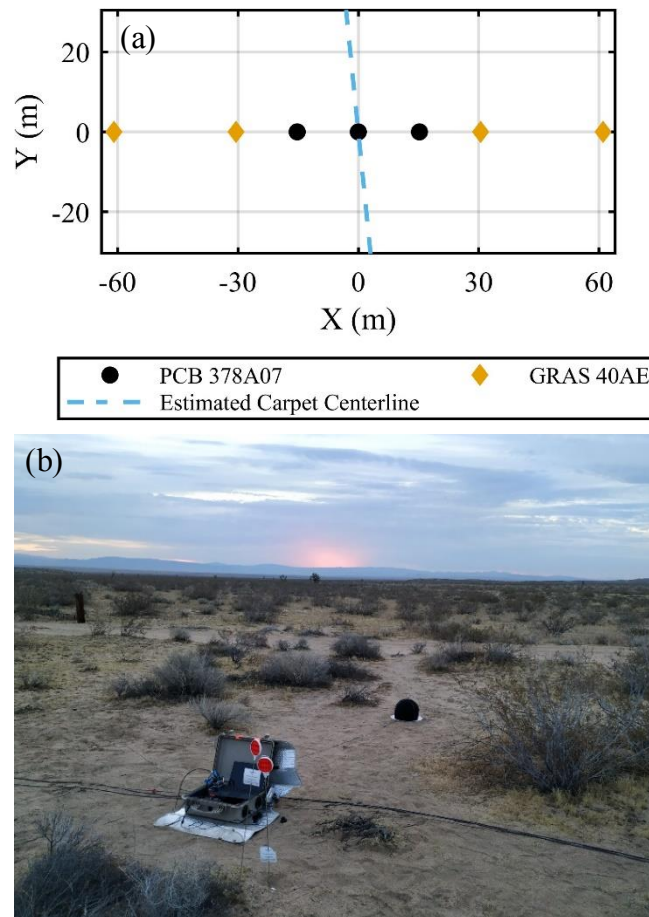


Figure 4.1 The microphone array deployed by BYU during the CarpetDIEM test campaign. (a) The microphone locations, indicating the two different microphone types deployed. (b) A photograph of the data acquisition unit and the center microphone.

(Stevens, 1972; Shepherd and Sullivan, 1991) by more than 0.5 dB, then those specific channels were removed from further analysis. Passes with fewer valid measurements have larger uncertainties (see Sec. 4.4 below) and are explicitly noted later in this chapter in Table 4.1. It is worth noting that the PCB 378A07 channels never experienced peak pressure clipping.

Figure 4.2 shows sonic boom data recorded at each microphone for a single pass. Subplot (a) shows all seven waveforms. Note that some are more rounded, and others are more spiked. These waveform characteristics have a direct impact on the spectrum, as shown in subplot (b). For example, the waveform measured at +60 m (200 ft) is more rounded and hence has less high-frequency content while the waveforms measured at -15 m (-50 ft) and -60 m (-200 ft) are more spiked and therefore have more high-frequency content. Although the spectra all agree well at frequencies below about 30 Hz, it is the high frequencies that primarily affect the human-perception metrics, as shown in subplot (c). These curves are the specific loudness spectra used during the calculation of the PL for

each boom. Note that the dominant frequencies are now around 50-1000 Hz, which coincides with much of the variability observed in subplot (b). Thus, atmospheric turbulence effects can drive large changes in the sonic boom human-perception metrics, as also observed by Bradley *et al.* (2020), Stout *et al.* (2021), and Carr *et al.* (2022).

4.3 Modeled Turbulence Parameters

Real-time turbulence measurements were not performed during the CarpetDIEM I test campaign. Thus, the parameters needed to model turbulence and weather effects on sonic booms with PCBoom and KZKFourier are obtained from two atmospheric models. The first is the Climate Forecast System Version 2 (CFSv2) model (Saha *et al.*, 2014) and the second is the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5 (ERA5) model (Hersbach *et al.*, 2020). From each model's freely-available data archive, the turbulence parameters needed for KZKFourier can be selected or derived by the user given a location and time span. As there is no conclusive answer for which of these two weather models is better suited for atmospheric turbulence relating to sonic booms (Doebler and Loubeau, 2023; Lympany and Page, 2024), both models are used throughout this chapter. This helps provide a sense of variability due to the choice of weather model, and no attempt will be made in this chapter to definitively state whether one model is more accurate than the other.

Among all the turbulence-related parameters, there are two that stand out as being of particular importance (Bradley *et al.*, 2020). These are the atmospheric boundary layer (ABL) height and the root-mean-square (rms) turbulence wind speed, denoted as σ_{vector} . Turbulence is often described as a split between scalar turbulence (temperature fluctuations) and vector turbulence (wind fluctuations), with both being accounted for in KZKFourier. Despite its name, the quantity σ_{vector} is a scalar, and the term “vector” denotes that this quantity is the standard deviation of the vector turbulence magnitude. This value is calculated from other quantities as (Bradley *et al.*, 2020; Wilson, 2000)

$$\sigma_{\text{vector}} = \sqrt{3.0u_*^2 + 0.35w_*^2}, \quad (4.1)$$

where u_* is the friction velocity and w_* is the mixed-layer velocity scale.

The CFSv2 and ERA5 models are directly compared over the duration of the CarpetDIEM I test campaign in Fig. 4.3. Subplot (a) shows the estimated ABL height as a function of time. The times of each of the six flights are indicated with the dashed red lines. The CFSv2 model tends to estimate an ABL height that is substantially greater than the prediction from ERA5, approaching a factor of two at some points in time. Subplot (b) shows the same type of comparison for σ_{vector} , which in both cases was calculated from the friction velocity and mixed-layer velocity scale as output by the models (Bradley *et al.*, 2020; Wilson, 2000).² CFSv2 again estimates greater values than ERA5, and the offset is more constant compared to the ABL height differences. It is important to note that because the CFSv2 model predicts higher values (and therefore higher overall turbulence),

²The mixed-layer velocity scale is not natively output from the models, but it can be derived using other native outputs (sensible heat flux, ABL height, surface pressure, and surface temperature).

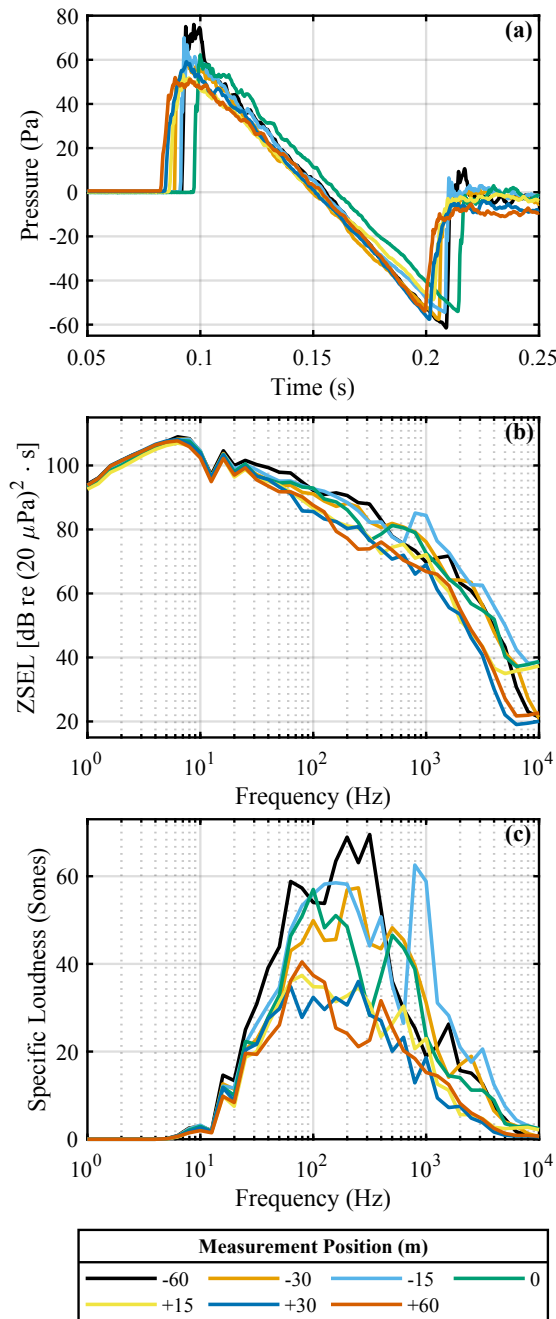


Figure 4.2 Sample data from one of the passes over the array. (a) The seven waveforms recorded across the array. (b) The flat-weighted sound exposure level spectrum corresponding to each waveform. (c) The loudness spectrum for each waveform.

simulations produced using the CFSv2 weather data are expected to have lower average metric values than the ERA5 results (Lonzaga, 2023). This is because higher turbulence is associated with longer mean rise times, which reduces the high-frequency content in the sonic booms (Lipkens and Blackstock, 1998). The higher turbulence values are also expected to affect the metric variability, but definitive predictions are hard to make beforehand because the variability increases and then decreases with propagation distance (Carr *et al.*, 2022).

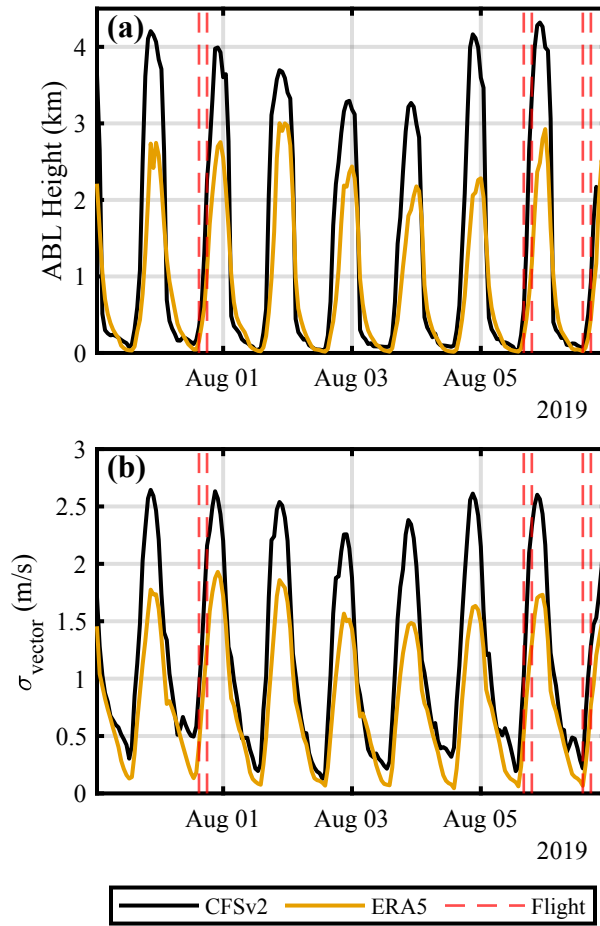


Figure 4.3 Comparing the CFSv2 and ERA5 weather model outputs for (a) atmospheric boundary layer height and (b) the standard deviation of the vector turbulence magnitude. Times of flights are indicated by the dashed red lines.

4.4 Quantifying Standard Deviation Uncertainty

Because stochastic quantities calculated using a finite number of measurements have inherent uncertainty, it is important to place confidence bounds on each of the results when using a

microphone array to estimate perception metric variability. This enables a fairer comparison between different turbulence array designs and different test campaigns. Although this was investigated for mean metric values as part of the SonicBAT program (Bradley *et al.*, 2020), it was not used to produce error bars on all results. In many cases, the variability due to atmospheric turbulence is reported as a standard deviation of measured quantities (Bradley *et al.*, 2020; Carr *et al.*, 2022; Averiyarov *et al.*, 2011; Stout *et al.*, 2021). In general, the confidence bounds on a standard deviation calculated using a finite number of data points is (Sheskin, 2000)

$$\sqrt{\frac{(n-1)s^2}{\chi^2_{[1-(\alpha/2)]}}} \leq \sigma \leq \sqrt{\frac{(n-1)s^2}{\chi^2_{(\alpha/2)}}}, \quad (4.2)$$

where σ is the true standard deviation of the population, s is the sample standard deviation calculated from the data, n is the number of data points, χ^2 represents the chi-square distribution, and α is the confidence ($\alpha = 0.05$ is used to calculate the 95% confidence interval). Note that Eq. (4.2) assumes an underlying normal distribution and that the values are randomly chosen from that distribution. While Eq. (4.2) can be used as-is to calculate the confidence bounds on the estimated standard deviation, additional insight can be gained by normalizing each term by the sample standard deviation,

$$\sqrt{\frac{(n-1)}{\chi^2_{[1-(\alpha/2)]}}} \leq \frac{\sigma}{s} \leq \sqrt{\frac{(n-1)}{\chi^2_{(\alpha/2)}}}, \quad (4.3)$$

This produces normalized multipliers σ/s , which are plotted as a function of the number of measurements in Fig. 4.4. This figure can be interpreted as follows: given the number of measurements for a supersonic pass across the turbulence array, one can determine the ratio σ/s for the 95% confidence upper and lower bounds. The values are then multiplied by the sample standard deviation to determine the upper and lower 95% confidence bounds on that standard deviation. For example, 10 measurements will have $\sigma/s = [0.688, 1.83]$, and if the sample standard deviation of those 10 measurements is 2.00, then the 95% confidence interval for $\sigma = [1.38, 3.65]$. If instead there were 1000 measurements with a sample standard deviation of 2.00, then $\sigma/s = [0.958, 1.05]$ and the 95% confidence interval for $\sigma = [1.92, 2.09]$. Note that the upper and lower bounds are not distributed symmetrically about the sample standard deviation.

This methodology relies on the assumption that the variability in the measurements is statistically random, which is an assumption that may be violated if the microphones are physically spaced too close to each other. Previous research by Roberts *et al.* (1967) indicates that 15 m (50 ft) spacing should be adequate to ensure that the turbulence distortions are sufficiently random. If this assumption can be met, then these methods can be used to create error bars on historical data, enabling a fair comparison between modern and historical turbulence array measurements.

The standard deviation confidence intervals defined in Eq. (4.2) rely only on the number of samples and the sample standard deviation. This enables retroactive confidence intervals to be placed on historical standard-deviation estimates, such as those from SonicBAT, as long as the number of samples is known and the microphone separation distance constraints are met. Bradley *et al.* (2020) report the standard deviations of three different metrics: PL, Indoor Sonic Boom

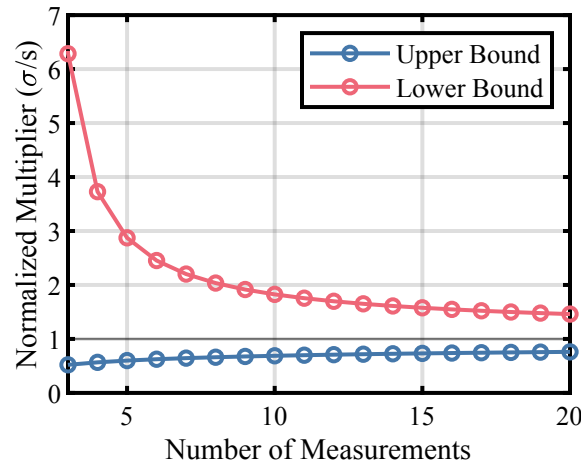


Figure 4.4 The normalized multipliers for the 95% confidence bounds on the standard deviation of a dataset with finite data points. These values are multiplied by the sample standard deviation to determine the extent of the 95% confidence bounds.

Annoyance Predictor (ISBAP), and peak overpressure ($P_{\max}$) as functions of RMS wind turbulence (σ_{vector}) and the propagation distance through turbulence. These results, along with their associated predictions produced during SonicBAT, are reproduced here in Fig. 4.5. Although some of the measurements had only 16 channels, others had 20 (with a minimum spacing of 10.1 m (33.3 ft)), so it is assumed that $n = 20$ in all cases. This means that the 95% confidence interval for the standard deviations has $\sigma/s = [0.76, 1.46]$. Each of the predictions had $n = 18,000$, meaning that $\sigma/s = [0.99, 1.01]$ and those confidence limits are not shown in Fig. 4.5 owing to their narrowness.

The retroactive error bars in Fig. 4.5 represent the uncertainty inherent in using a finite number of measurements to estimate the standard deviation. The only way to make these confidence bounds narrower (i.e., obtain a tighter σ/s interval) is to use more measurements. Including these uncertainty limits enables fair comparisons between different array designs used during different historical, modern, and future test campaigns. Note that the measurement uncertainty presented here does not account for other sources of uncertainty, such as microphone calibration, ambient environmental conditions, background noise, windscreen insertion loss, and data acquisition system settings (Klos, 2025).

4.5 CarpetDIEM I Metric Variability

Turbulence-induced variability has a strong impact on human-perception metric values (Bradley *et al.*, 2020; Stout, 2018; Doeblner, 2017; Durrant *et al.*, 2022b). The variability observed on a per-boom basis during CarpetDIEM I at the small linear turbulence array is shown in Table 4.1. The estimated RMS wind turbulence (σ_{vector}) and propagation distance through turbulence (accounting for ray elevation angle) are shown using both the CFSv2 and ERA5 models. The propagation

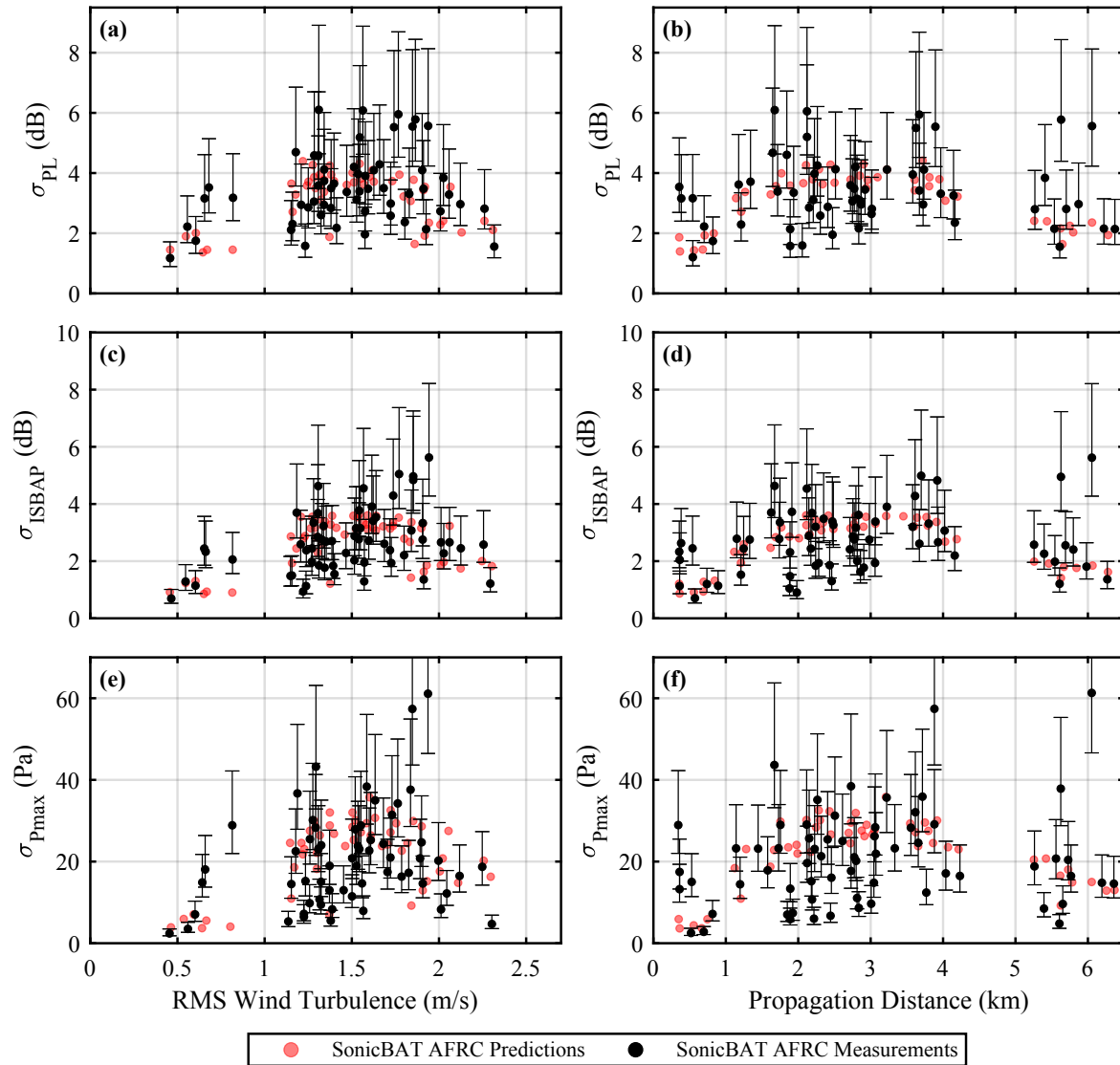


Figure 4.5 Placing retroactive error bars to account for the finite number of measurements on results from the SonicBAT test campaign using data measured at NASA’s Armstrong Flight Research Center (AFRC). The PL standard deviation is shown as a function of (a) RMS wind turbulence and (b) propagation distance through the ABL. The measurements are compared directly against predictions made for the SonicBAT conditions. Subplots (c) and (d) show the same results for the ISBAP metric while (e) and (f) show the same results for the peak overpressure.

distance through turbulence is estimated following the method of Stout (2018) (see Fig. 3-1 therein), using the ray elevation angle and ABL height to compute the straight-line distance between the PCBoom-predicted position of the ray at the top of the ABL and its ground intersection. The stratified atmospheric data used in PCBoom were measured by a weather balloon radiosonde (Vaisala, 2017). Additionally, the number of microphones used for each measurement is included. The means for PL (dB), ISBAP (dB), and Pmax (psf, with 1 psf = 47.88 Pascals) are shown along with their associated 95% confidence intervals. The standard deviations for these three metrics are also shown, along with their σ/s intervals, which are identical across all the metrics because the intervals only depend on the sample size and the desired confidence limits.

4.6 Comparison with Simulations

To best ascertain whether the state-of-the-art in sonic boom modeling accurately captures the variability observed in the measurements, simulations were performed according to the flowchart shown in Fig. 4.6. Simulations were performed using a combination of the Enhanced Burgers module of PCBoom 7.4 (Lonzaga *et al.*, 2022) and KZKFourier. As-flown aircraft trajectories coupled with near-field computational fluid dynamics simulations (similar to Loubeau and Doeblér (2019)) and stratified atmospheric data from weather balloon radiosonde measurements were input into PCBoom to predict the sonic boom waveform and entry angle when the boom entered the atmospheric boundary layer. This waveform was then used as an input for KZKFourier, which was used in its two-dimensional mode to produce distorted waveforms every 0.5 m along a 500-m span. Although KZKFourier can be run in a three-dimensional mode (Stout and Sparrow, 2019), these simulations were performed in two dimensions to reduce the prohibitively high computational expense of running the simulations in three dimensions (Stout, 2018). For both weather models, 20 turbulence realizations were produced, resulting in 20 simulations over 500 m for each pass with each weather model. Assuming that each of the 20 turbulence realizations produced statistically similar results on the ground, the 20 simulations were concatenated to produce an effective 10,000-m aperture. Although this would be inappropriate if looking at metric derivatives across the array, it is assumed that this approach is valid when looking only at the mean and standard deviations of the 20 combined simulations.

Simulation results using both CFSv2 and ERA5 weather models are compared directly against measurements in Figs. 4.7 and 4.8, respectively. In subplot (a), the mean PL values for each boom measured across the seven-microphone array are compared against the simulations and in subplot (b), the standard deviations are likewise compared. Figures 4.7 and 4.8 also show the measurements and predictions as functions of propagation distance through turbulence (c-d) and RMS wind turbulence (e-f), which is identical to σ_{vector} (see Sec. 4.3). Note that although the horizontal axis limits are changed between Figs. 4.7 and 4.8 (to better show the results), the measured data are identical in both figures. The simulated results show clear trends of decreasing mean PL and increasing PL standard deviation with increasing propagation distance and RMS wind turbulence. However, these same trends are not obvious in the measured data, perhaps because the uncertainties (due to finite

Table 4.1 Model parameters and measurement results from the seven-microphone linear turbulence array deployed during CarpetDIEM I. All confidence bounds are 95%.

Pass	RMS Wind Turbulence (m/s)		Propagation Distance (m)		Ray Elevation Angle (Deg.)		Mics Used	Mean PL	Mean ISBAP	Mean Pmax	σ/s	σ_{PL}	σ_{ISBAP}	σ_{Pmax}
	CFSv2	ERA5	CFSv2	ERA5	CFSv2	ERA5								
1	0.99	0.49	800	405	29.7	29.5	7	104.7 ± 1.2	112.0 ± 0.7	1.91 ± 0.16	[0.644, 2.202]	1.3	0.7	0.17
2	1.03	0.53	848	446	30.1	29.9	6	104.4 ± 4.0	111.6 ± 2.4	1.73 ± 0.45	[0.624, 2.453]	3.8	2.3	0.43
3	1.07	0.57	918	500	29.9	29.7	6	102.7 ± 4.3	110.0 ± 3.1	1.63 ± 0.20	[0.624, 2.453]	4.1	2.9	0.20
4	1.11	0.61	1014	568	29.0	28.8	7	99.7 ± 3.3	107.6 ± 1.7	1.31 ± 0.04	[0.644, 2.202]	3.5	1.8	0.05
5	2.20	1.35	4744	2419	30.2	30.1	7	102.9 ± 1.0	110.6 ± 0.7	1.78 ± 0.12	[0.644, 2.202]	1.1	0.8	0.13
6	2.21	1.39	4859	2589	30.2	30.1	7	100.9 ± 1.6	108.5 ± 0.8	1.49 ± 0.15	[0.644, 2.202]	1.7	0.8	0.16
7	2.23	1.44	4773	2655	31.5	31.4	7	105.7 ± 4.3	113.0 ± 3.0	2.07 ± 0.35	[0.644, 2.202]	4.6	3.3	0.37
8	2.24	1.47	4985	2863	30.6	30.4	7	105.4 ± 3.2	113.0 ± 2.2	2.30 ± 0.45	[0.644, 2.202]	3.4	2.4	0.48
9	1.25	0.67	1784	620	29.0	29.8	6	103.5 ± 1.5	110.8 ± 1.7	1.67 ± 0.30	[0.624, 2.453]	1.5	1.6	0.29
10	1.32	0.71	1992	672	29.4	30.2	5	107.3 ± 1.6	113.9 ± 0.8	2.07 ± 0.13	[0.599, 2.874]	1.3	0.6	0.10
11	1.38	0.75	2196	723	29.8	30.6	7	99.2 ± 3.4	107.2 ± 2.4	1.28 ± 0.17	[0.644, 2.202]	3.7	2.6	0.18
12	1.45	0.78	2504	845	28.6	27.9	7	104.5 ± 3.4	111.6 ± 2.1	1.73 ± 0.16	[0.690, 1.915]	3.7	2.3	0.17
13	2.39	1.38	7777	2924	27.2	27.3	6	104.4 ± 4.4	113.3 ± 3.9	2.68 ± 0.76	[0.624, 2.453]	4.2	3.7	0.72
14	2.41	1.41	7684	2994	28.3	28.3	7	101.7 ± 3.3	109.4 ± 2.8	1.75 ± 0.29	[0.644, 2.202]	3.6	3.0	0.31
15	2.43	1.44	8057	3253	27.5	27.5	7	107.4 ± 4.6	114.7 ± 3.2	2.31 ± 0.51	[0.644, 2.202]	4.9	3.4	0.55
16	2.45	1.47	7444	3139	30.6	30.3	3	113.1 ± 7.9	120.1 ± 4.6	4.33 ± 0.89	[0.521, 6.285]	3.2	1.9	0.36
17	0.32	0.10	185	71	26.5	26.5	7	103.9 ± 0.8	112.1 ± 0.5	1.97 ± 0.09	[0.644, 2.202]	0.8	0.5	0.09
18	0.39	0.13	239	80	27.5	27.5	5	108.2 ± 2.1	115.2 ± 1.3	2.16 ± 0.30	[0.599, 2.874]	1.7	1.1	0.24
19	0.46	0.15	311	94	27.1	27.1	5	111.9 ± 4.5	118.1 ± 2.9	2.77 ± 0.85	[0.599, 2.874]	3.6	2.4	0.68
20	1.37	0.84	2670	1315	26.9	26.6	7	91.8 ± 1.5	102.3 ± 1.1	1.13 ± 0.06	[0.644, 2.202]	1.6	1.1	0.07
21	1.39	0.86	2582	1258	30.5	30.2	7	103.2 ± 2.6	110.5 ± 1.6	1.54 ± 0.14	[0.644, 2.202]	2.8	1.7	0.15
22	1.41	0.88	2837	1366	30.1	29.7	7	98.2 ± 1.2	106.9 ± 1.0	1.45 ± 0.08	[0.644, 2.202]	1.3	1.1	0.08
23	1.43	0.89	3060	1475	29.6	29.3	7	99.8 ± 1.7	108.8 ± 1.1	1.79 ± 0.20	[0.644, 2.202]	1.9	1.1	0.22

number of measurements) are so large. This suggests a need to use more microphones in the future to assess turbulence trends in measured data.

These large uncertainties due to the finite number of measurements should be favorable for comparing the predictions to the measured data because there is a greater chance that the predicted value will fall within the uncertainties, however it is noted that this is a finite-measurement effect that would not hold if more measurements are used. The mean and standard deviation prediction success using both weather models are compared for all metrics (Loubeau and Page, 2018) in Fig. 4.9. Metric prediction success is defined as the simulation falling within the 95% confidence intervals for the measurement (i.e., the black bars in Fig. 4.7, but calculated individually for each metric). Across metrics, the two weather models accurately predict the mean measured value in about 25–55% of the cases. The standard deviation is somewhat better predicted, at about 30–70% success, but neither the means nor standard deviations are predicted consistently with great accuracy. Thus, even with large uncertainties, the PCBoom+KZKFourier model, using CFSv2 and ERA5 data, struggles to accurately predict the measured variability.

If instead, the 99% confidence intervals are used for the measurements, the results are as shown in Fig. 4.10. The mean values are better predicted using the ERA5 data, with a mean around 50–80% compared to the 30–60% success rate when using the CFSv2 data. However, the relative success is metric-dependent for the standard deviation, with both weather models producing results

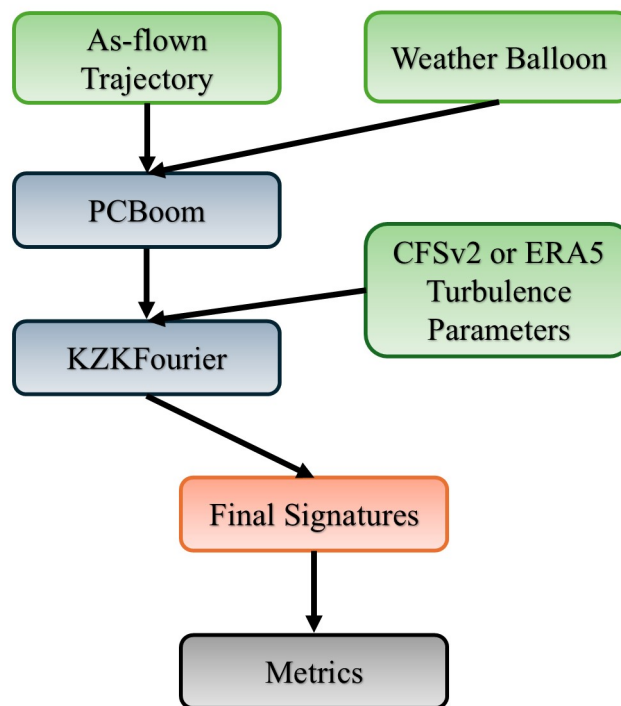


Figure 4.6 A schematic for the process of producing the final metrics.

that average around 50–80%. It is noted however that the success rate when using the measured 99% confidence intervals is a direct result of the confidence intervals being wider. Further research needs to determine a suitable confidence threshold for mean and standard deviation metric values across sonic boom array measurements. Such a suitable threshold will need to balance accuracy in the predictions with uncertainty in the atmospheric measurements.

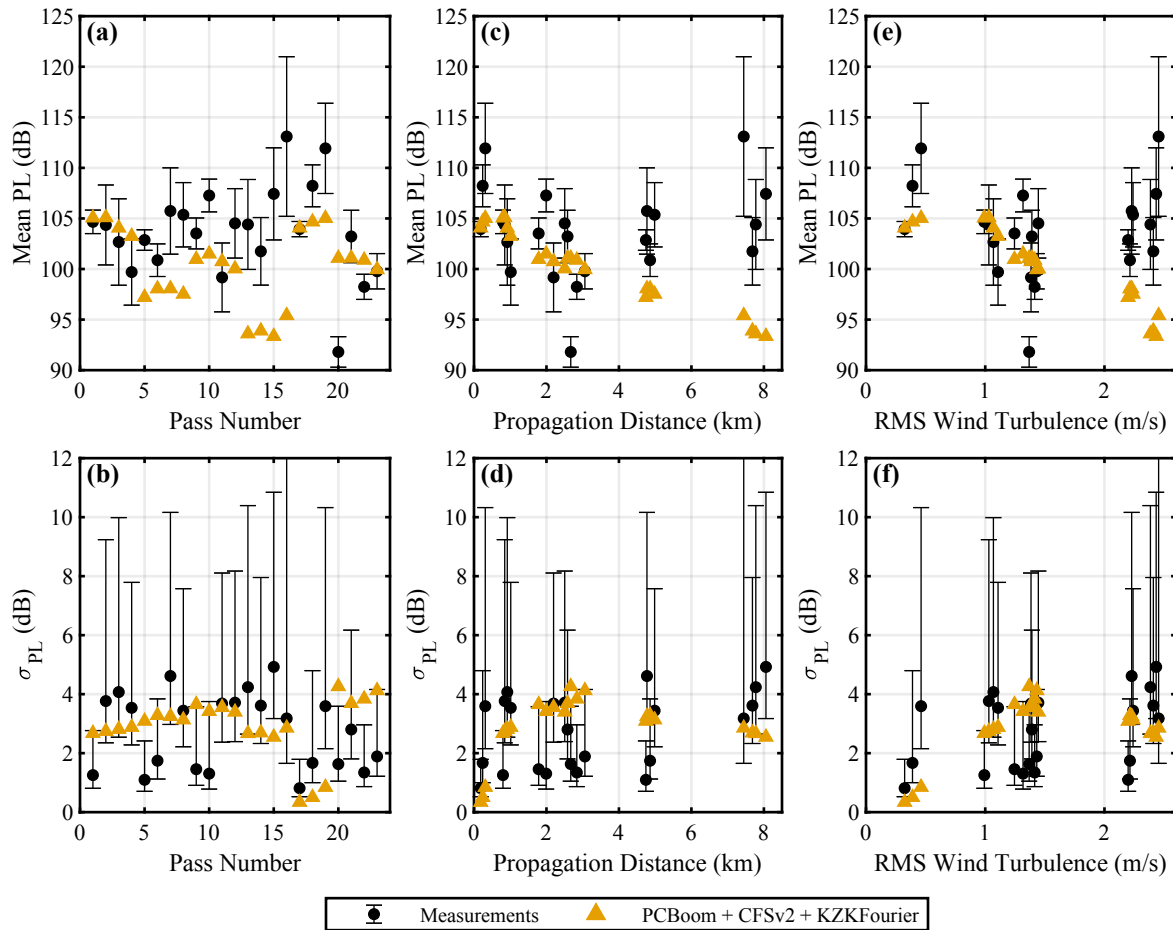


Figure 4.7 Comparison between the measurements, PCBoom+CFSv2+KZKFourier predictions, as functions of pass number, propagation distance through turbulence, and RMS wind turbulence. The mean PL (a, c, e) and the standard deviation (b, d, f) are directly compared, including vertical error bars on the measurements that arise from the finite number of measurements (see Sec. 4.3).

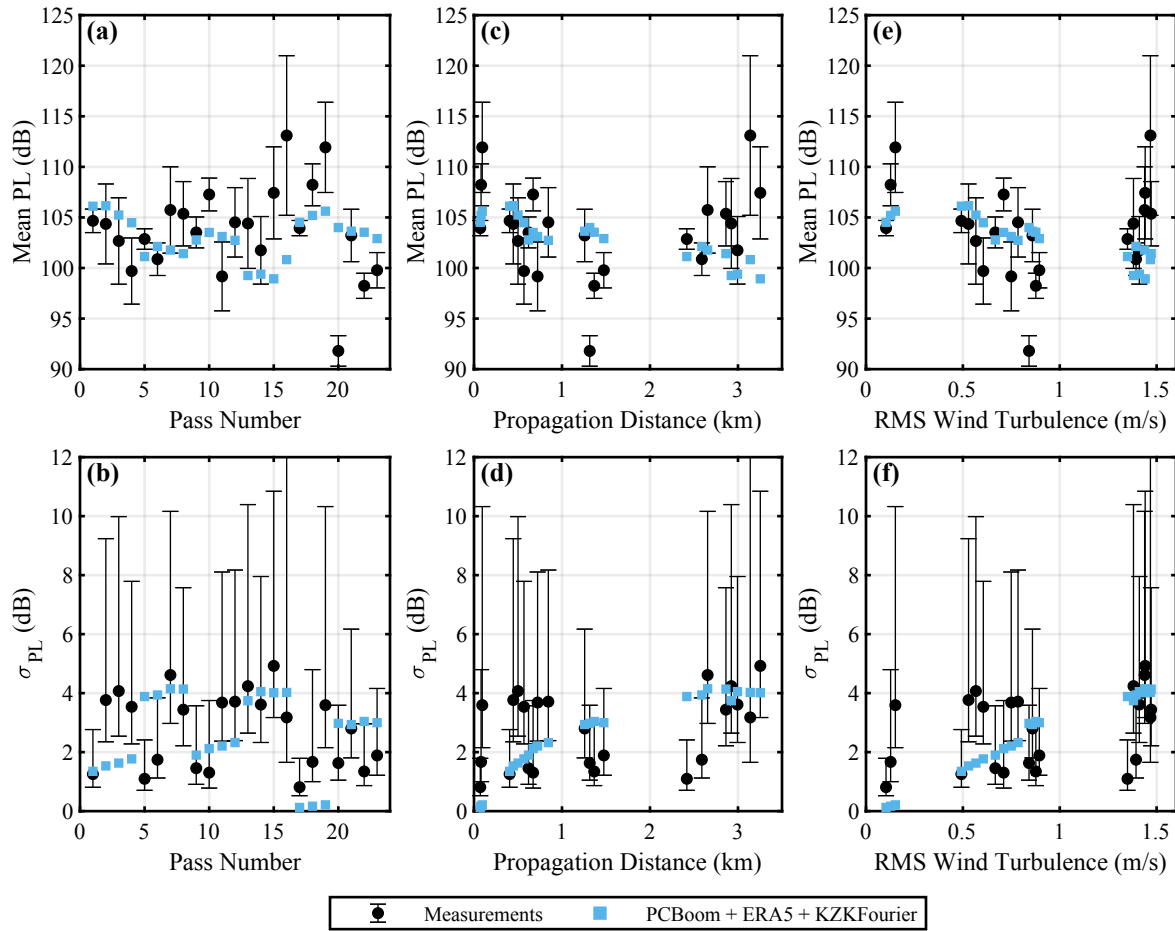


Figure 4.8 Comparison between the measurements, PCBoom+ERA5+KZKFourier predictions, as functions of pass number, propagation distance through turbulence, and RMS wind turbulence. The mean PL (a, c, e) and the standard deviation (b, d, f) are directly compared, including vertical error bars on the measurements that arise from the finite number of measurements (see Sec. 4.3).

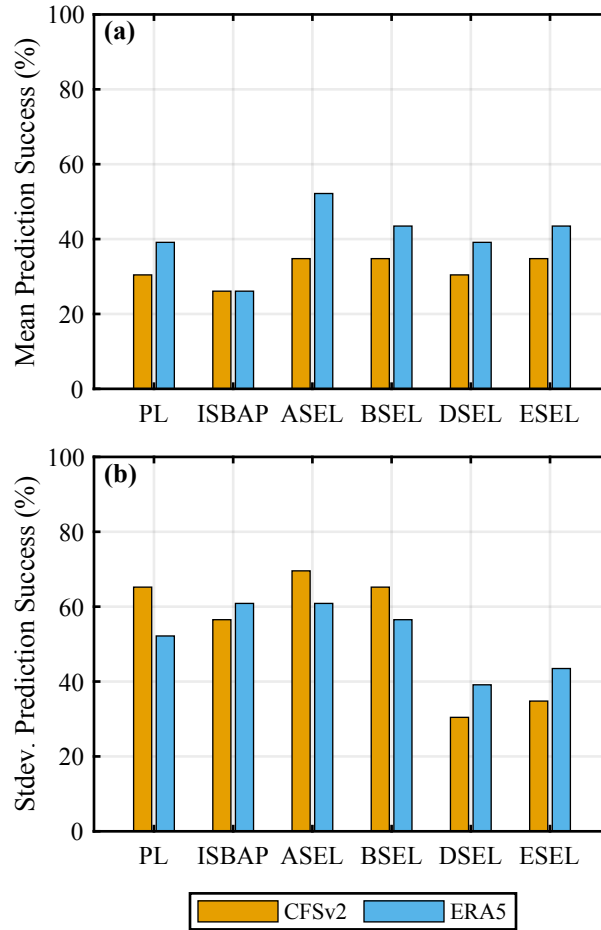


Figure 4.9 The prediction success of the PCBoom + KZKFourier + CFSv2 and PCBoom + KZKFourier + ERA5 models, compared to measurements for the (a) mean and (b) standard deviation of each metric. Success is defined by the prediction falling within the 95% confidence region for the measurements estimated using Eq. (4.2).

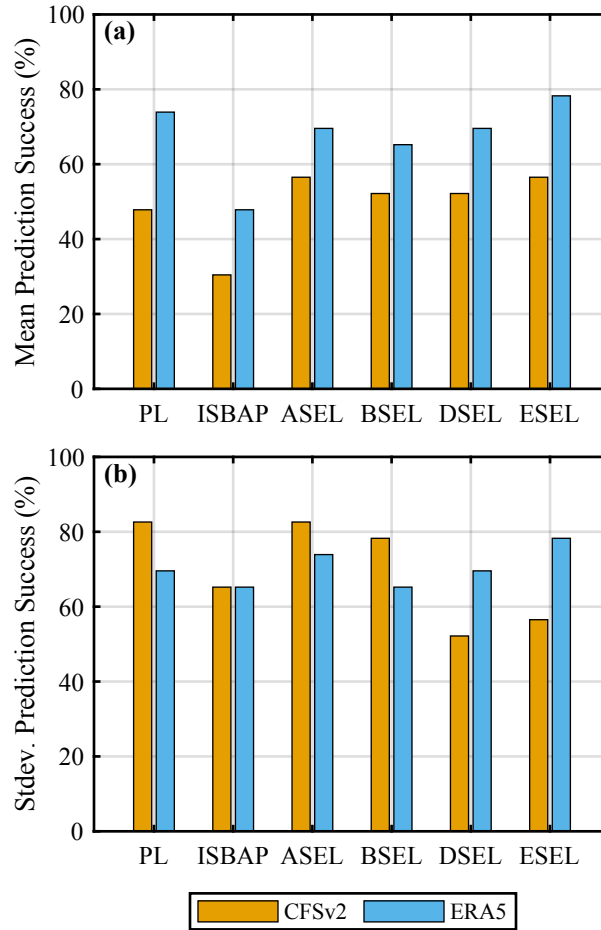


Figure 4.10 The prediction success of the PCBoom + KZKFourier + CFSv2 and PCBoom + KZKFourier + ERA5 models, compared to measurements for the (a) mean and (b) standard deviation of each metric. Success is defined by the prediction falling within the 99% confidence region for the measurements estimated using Eq. (4.2).

4.7 Conclusion

Measurements from a seven-microphone turbulence array deployed during the NASA CarpetDIEM I sonic boom test campaign are shown and compared against the current state-of-the-art modeling techniques. These models include PCBoom (using as-flown trajectory data and measured weather balloon data) for signature evolution and propagation until the booms reach the atmospheric boundary layer. KZKFourier is then used to model propagation through the atmospheric boundary layer, with meteorological parameters modeled using CFSv2 and ERA5.

A method for calculating error bars to be placed on metric standard deviations is proposed and recommended for future use. This method relies only on the number of microphones and assumes that they are spaced sufficiently far apart so that the turbulence effects are random. For historical measurement arrays that meet this randomness criterion, retroactive error bars can be placed on the standard deviations, and this is demonstrated using data extracted from the NASA SonicBAT final report (Bradley *et al.*, 2020).

When comparing the measured CarpetDIEM I results to the state-of-the-art models, the prediction accuracy falls within about 25–70%, varying across metric type. This means that only 25–70% of modeled results fall within the 95% confidence intervals associated with the seven-microphone array. If more microphones had been used in the physical measurements, the measurement error bars would have been tighter and thus the prediction accuracy could have been less. At present, it is not yet known which of the models or model inputs (PCBoom, KZKFourier, or CFSv2/ERA5) needs the most immediate attention to improve prediction accuracy.

As applied to the CarpetDIEM I dataset, the combined models of PCBoom, KZKFourier, and CFSv2/ERA5 have limitations in predicting sonic boom metric variability due to atmospheric turbulence. This will become increasingly important as measurements are made of low-boom aircraft and decisions will need to be made about how to distribute microphones across the measurement domain. It is strongly recommended to obtain simultaneous turbulence and other meteorological measurements during the flights along with accurate near-field pressure data around the aircraft, as those could improve the prediction accuracy.

Acknowledgments

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4.8 Chapter Appendix: Minor Peak-pressure Clipping Effects on Sonic Boom Metrics

Owing to hardware limitations, the seven-microphone turbulence array used two different ½-inch microphone types. The three center microphones were PCB 378A07 type while the four outer microphones (two on each end of the array) were GRAS 46AE type. Because the GRAS 46AE microphones have a higher sensitivity (~50 mV/Pa) relative to the PCB 378A07 (~5 mV/Pa), these channels were more susceptible to peak-pressure clipping. Two examples are shown in Fig. 4.11. All minorly clipped booms, like Example (a), were deemed to be minimally affected by the clipping and were analyzed alongside other booms in this chapter. All majorly clipped booms, like Example (b), were deemed to be too clipped to enable reliable metric calculations and were thus excluded from further analysis in this chapter.

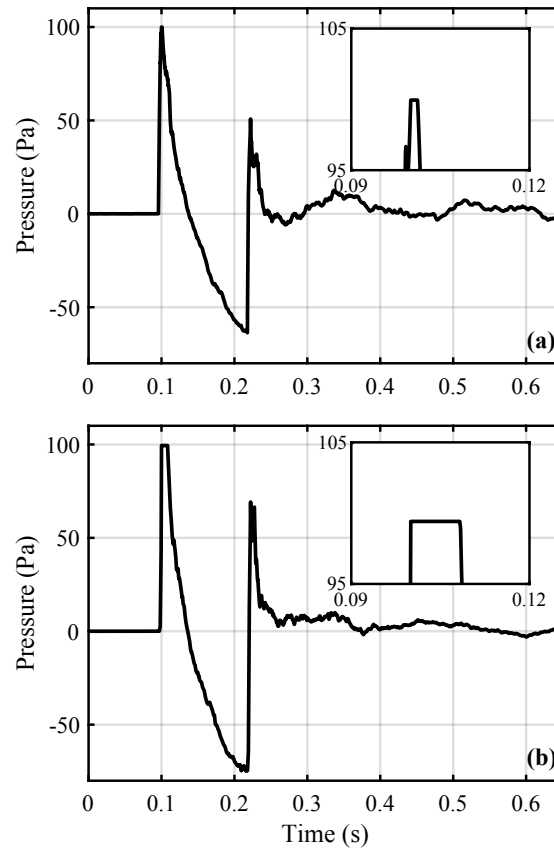


Figure 4.11 Sample clipped boom measurements for booms that were deemed (a) “minorly clipped” and (b) “majorly clipped.” The majorly-clipped booms were not used in analyses in this chapter, while the minorly-clipped booms were analyzed alongside the unclipped measurements.

The thresholds for “minor” and “major” clipping were chosen based on work by Gee *et al.* (2024a), where unclipped waveforms were artificially clipped to determine the impact on metric values. A summary plot for the effects of peak pressure clipping on the PL metric is shown in Fig. 4.12. For this analysis, unclipped booms from across the CarpetDIEM I array were used. Each boom was clipped to a percentage of the peak pressure, metrics were calculated, and then the boom was clipped to a lower peak pressure. The process was repeated for each boom all the way from no clipping (0%) to highly clipped (80%). The gray dots correspond to a single measurement trimmed to a single clipping percentage. The green bars denote two standard deviations for the variability in PL across all booms at each clipping percentage. The blue bars denote the mean change in PL at each clipping percentage. Based on this analysis, booms that were clipped to within an estimated 20% of their peak overpressure were deemed “minorly clipped”, like Example (a) in Fig. 4.11. All booms with more than 20% clipping (approximately equal to less than a 0.5-dB change in metric value) relative to the estimated peak overpressure, like Example (b) in Fig. 4.11, were deemed “majorly clipped” and were not used in the analyses in this chapter. This threshold of 20% is fairly arbitrary, and future work could go toward determining a more precise threshold.

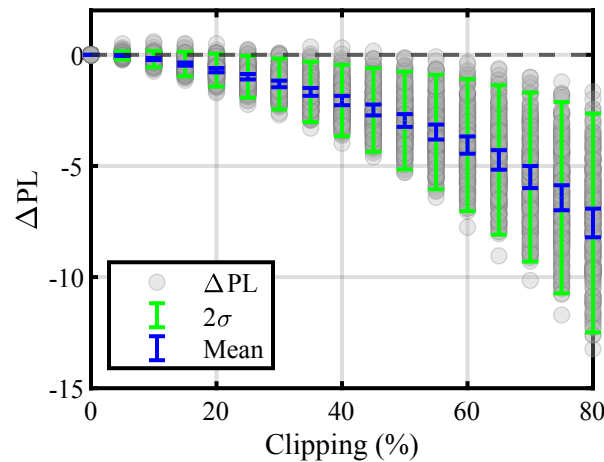


Figure 4.12 Reduction in metric level (ΔPL) due to applying increasing percentages of artificial peak-pressure clipping to the unclipped booms measured across the entire CarpetDIEM I array.

Chapter 5

Best Practices for Sonic Boom Measurements

Abstract

¹As part of its Quesst mission, NASA will fly the supersonic X-59 aircraft over communities to assess human annoyance to quieter sonic booms. As preparation for this flight test campaign continues, there are still many unanswered questions regarding best practices for sonic boom measurements inside and outside communities. This paper features sonic boom measurement and signal processing information including time-domain windowing, zero padding, digital pole-shift filtering, ground-based vs. elevated microphones, atmospheric turbulence, and contaminating noise mitigation. This work both summarizes previous recommendations and provides new recommendations for sonic boom measurement and signal processing. Thus, this paper serves as an overview of the research and recommendations.

¹This chapter is derived from a paper published in the Proceedings of Meetings on Acoustics with the following citation:

Anderson, M. C., Gee, K. L., Durrant, J. T., Loubeau, A., Doebler, W. J., Klos, J. (2024), “Recommendations for sonic boom community noise testing measurement and analysis.” *Proc. Mtgs. Acoust.* 50 (1): 040008. <https://doi.org/10.1121/2.0001902>

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5.1 Introduction

As part of its Quesst mission, NASA will demonstrate quiet supersonic aircraft technology (NASA, 2026). This mission will feature a new aircraft, the X-59, that is designed to cruise at Mach 1.4 while producing a substantially quieter sonic boom, often referred to as a “low-boom”, than previous aircraft (Loubeau and Page, 2018). To determine the human response to low booms, the X-59 will overfly several different communities across the USA, and local residents will fill out surveys indicating their level of annoyance to each event, similar to previous test campaigns (Page *et al.*, 2014, 2020). These survey results will then be combined with acoustic data on the ground to determine a dose-response relationship (Lee *et al.*, 2020) that indicates a relationship between metric levels and human annoyance. The final results will then be delivered to regulators to inform decisions on the future of overland commercial supersonic flight.

Over the past several decades, numerous theoretical advancements have helped develop the theory required to design a low-boom aircraft like the X-59 (Maglieri *et al.*, 2014). For the X-59 tests, it is imperative to collect acoustic data that are both precise and accurate. One particular challenge is that the measurements of low booms are more susceptible to ambient and instrumentation noise contamination than classical, high-amplitude N-waves. Additionally, the sonic boom perception metrics of interest (Loubeau and Page, 2018) are frequency-dependent and can be sensitive to contaminating noise and turbulence effects. These metrics, discussed in Loubeau and Page (2018), are the Perceived Level (PL) (Stevens, 1972; Shepherd and Sullivan, 1991), the Indoor Sonic Boom Annoyance Predictor (ISBAP), and the A-, B-, D-, and E-weighted sound exposure levels (SEL).

Brigham Young University (BYU) has been working with NASA to determine appropriate measurement and analysis techniques for sonic booms to help overcome some of these challenges. This chapter summarizes prior research and newer analyses. The following topics are discussed in subsequent sections:

- Time-domain windowing
- Zero-padding prior to FFT analyses
- Digital pole-shift filtering
- Ground-based vs. elevated microphones
- Atmospheric turbulence
- Contaminating noise removal

5.2 Windowing

One of the many factors to consider when analyzing sonic boom recordings is time-domain windowing prior to performing a fast Fourier transform (FFT)-based spectral analysis. Windowing ensures that the waveform endpoints are set to zero, thereby reducing spectral leakage due to

discontinuities at the waveform end points. One useful window choice is a Tukey (or tapered cosine) window because it leaves most of the waveform unaffected. The ramp portions of this window are defined by cosine functions, and the lengths of the ramp portions are defined by the “cosine fraction.” This is illustrated in Fig. 5.1. As an example, a cosine fraction of 0.4 indicates that each ramp individually covers 20% of the waveform, for a total of 40% of the waveform being tapered. Thus, the percentage of the waveform tapered by each individual ramp is determined by dividing the cosine fraction by two and multiplying by one hundred. In the limit that the cosine fraction becomes zero, the Tukey window becomes a rectangular window. In the limit that the cosine fraction becomes unity, the Tukey window becomes a Hann window. A cosine fraction of 0.1 is recommended for sonic boom analyses where waveforms start 100 ms before the peak of the primary shock and the total recording length is 650 ms, as shown in Fig. 5.2(a) and (c). This recording length convention is the same as used in Page *et al.* (2014), though the lead time of 100 ms recommended here is shorter than in Page *et al.* (2014). This captures more of the post-boom noise if that is of interest to a particular analysis.

The choice of cosine fraction is relatively unimportant as long as the window is not too rectangular, and the ramps do not attenuate the main shocks. The effects of different cosine fractions on sonic boom metrics can be studied directly, as is shown in Fig. 5.2. In this example, sonic boom metrics are calculated with varying cosine fractions. Figure 5.2(a) shows an example 650-ms boom recording from the NASA Carpet Determination in Entirety Measurements I (CarpetDIEM I) test campaign (Durrant *et al.*, 2022b) along with a reference Tukey window using a cosine fraction of 0.1. Figure 5.2(b) shows the results of applying different cosine fractions and displays the results for each metric relative to a cosine fraction of 0.1, i.e., metric computed with a given cosine fraction minus metric computed with a 0.1 cosine fraction. This was done to visualize differences more easily for each metric simultaneously. The same analysis is shown for another boom, from the NASA Quiet Supersonic Flights 2018 (QSF18) test campaign (Page *et al.*, 2020; Anderson *et al.*, 2022b), in Fig. 5.2(c) and (d). The two examples are included to demonstrate that the results are similar for booms that have different relative amounts of post-boom noise. For both waveforms, the metric values all have a region of relative flatness between a cosine fraction of about 0.05 to 0.3. Divergences from this flat region at small cosine fractions are likely due to the window being too rectangular and causing waveform edge discontinuity, especially for the boom in Fig. 5.2(c), which has notable post-boom noise and has a lower metric value, making it more sensitive to the discontinuity. This is because a nearly rectangular window will introduce broadband noise into the spectrum, increasing the metric value. Notice how for both booms, the metrics all diverge simultaneously at and above a cosine fraction of 0.3. For this particular cosine fraction, the individual ramp lengths are $0.3/2 \times 650 \text{ ms} = 97.5 \text{ ms}$, which means that the initial ramp will start reducing the primary shock amplitude. For waveforms with 100 ms of lead time before the peak of the primary shock and a total duration of 650 ms, a cosine fraction of 0.1 seems to be a suitable choice.

An asymmetric window may also be desirable, where the second ramp is longer than the first (Klos, 2022). This would enable an even more gradual taper to zero for the post-boom noise. This window type is analyzed in Fig. 5.3. Part (a) shows the same boom as analyzed in Fig. 5.2(c) and (d), but with an example asymmetric window superposed on top of the waveform. Part (b) shows the same type of analysis as Fig. 5.2, but where the first ramp is kept at a cosine fraction

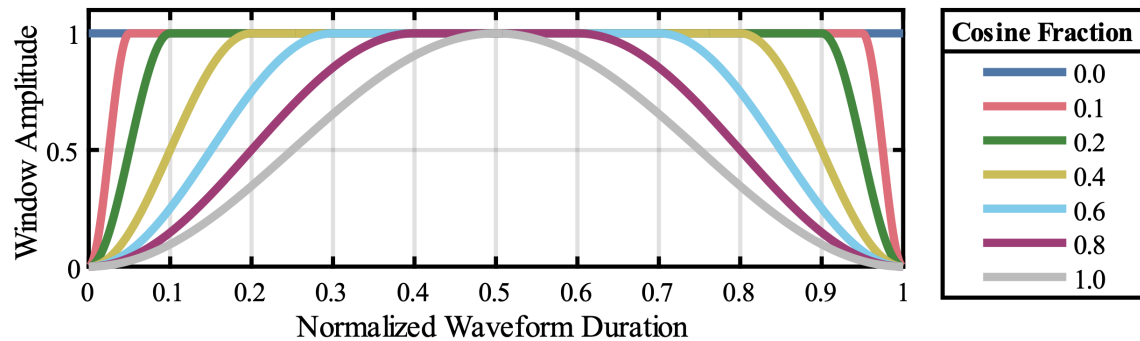


Figure 5.1 Several example Tukey windows, each with a different cosine fraction. A rectangular window is produced when the cosine fraction is zero, and a Hann window is produced by setting the cosine fraction to unity.

of 0.1 (covering 5% of the recording) and only the second ramp cosine fraction is varied between 0–0.5 (0–25% of the recording). Evidently, increasing the second ramp length has marginal effects on the metric values, so long as its cosine fraction is greater than about 0.05 (2.5% of the recording). Therefore, an asymmetric window is also a good choice when analyzing sonic booms, though for this example it is not necessarily better than a symmetric window.

There likely exist other acceptable windows that could be successfully applied to sonic boom waveforms. Overall, the choice of window appears to be relatively unimportant so long as the primary boom is not affected by the windowing. In other words, the post-boom noise is a small contribution to the metric values, and a cosine fraction of 0.5 (25% of the recording) for the latter half of the waveform only has a 0.25 dB impact. This also implies that the window gain is negligible compared to the primary boom signal, which is not affected by the window. Further research could be performed to determine whether the claims in this section hold true for recordings with lower signal-to-noise ratios.

5.3 Zero Padding

When performing an FFT analysis over a short time interval, the frequency resolution is sparser than for a longer time interval. When converting the spectrum into one-third octave (OTO) bands, this sparse frequency resolution results in a nonphysical distribution of energy in adjacent OTO bands at low frequencies. An example is the spectrum shown in Fig. 5.4(a). Notice the jagged peaks and troughs in the spectrum below 10 Hz. A solution to this issue is to use a longer recording to increase the frequency resolution and distribute a proper proportion of energy into each OTO band. For sonic boom recordings, this can be accomplished through zero padding. After windowing the signal, zeros are artificially appended (and/or prepended) onto the waveform, creating a longer recording. Because the sonic boom is a one-time impulse event, and many sonic boom metrics are exposure metrics, adding zeros to the signal does not affect those final metric values.

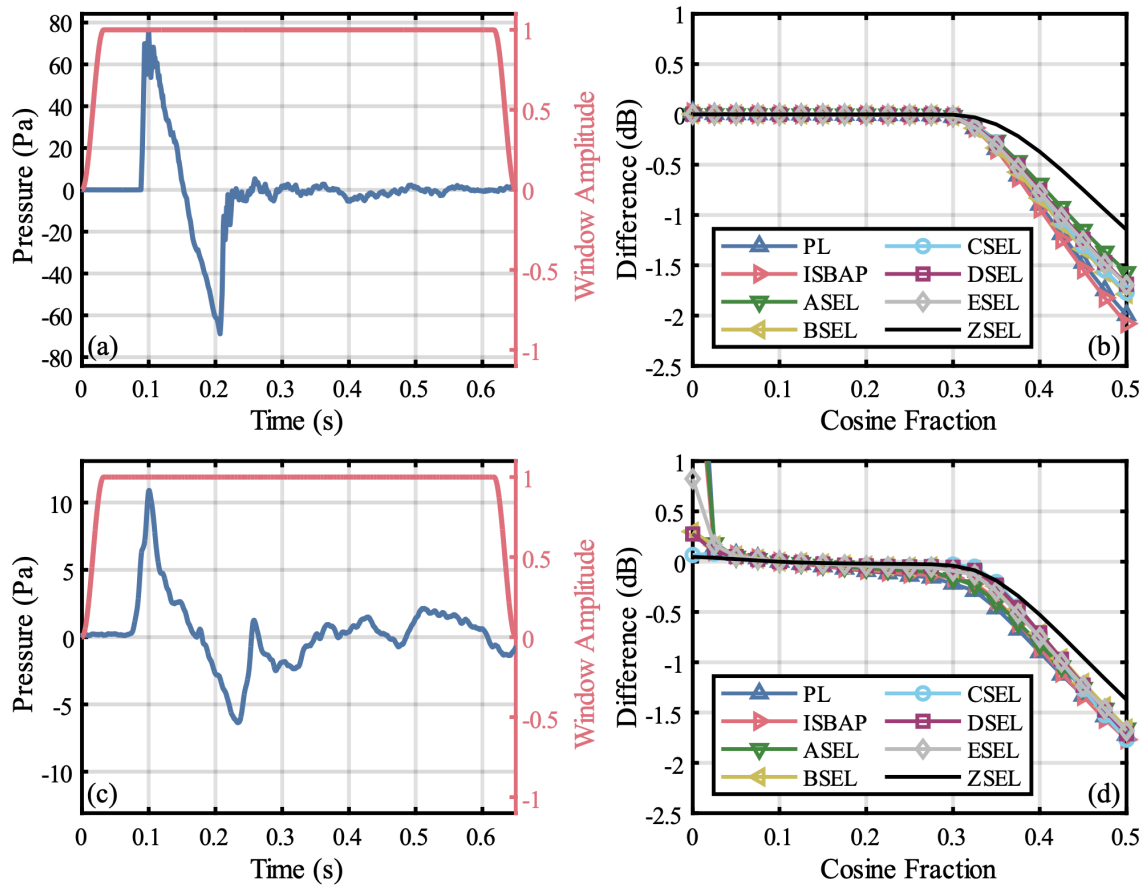


Figure 5.2 The effects of different cosine fractions on sonic boom perception metric values. (a) An example waveform from CarpetDIEM I along with a reference Tukey window with a cosine fraction of 0.1. (b) All sonic boom metrics shown relative to their calculated values with a cosine fraction of 0.1. (c) Similar to (a) but using a boom from QSF18 with notable post-boom noise. (d) Similar to (b) but using the QSF18 boom.

To determine the total duration of the padding required to remove the jagged peaks in the low-frequency spectrum, spectra of waveforms with increasing pad lengths were computed, and the results are shown in Fig. 5.4(b). This analysis demonstrates that a pad of four seconds, resulting in a padded waveform of total duration 4.650 seconds, is a good choice to smooth the spectrum down to 1 Hz. Larger padding will always produce even smoother results but is more computationally time-consuming for FFT calculations. Therefore, we recommend applying up to four seconds of zero-padding to the windowed waveform before performing an FFT, if smooth FFT results are desired. An example is shown in Fig. 5.5, where the four seconds of padding is split with two seconds before and two seconds after the windowed waveform. This could also be applied as four seconds either before or after the recording.

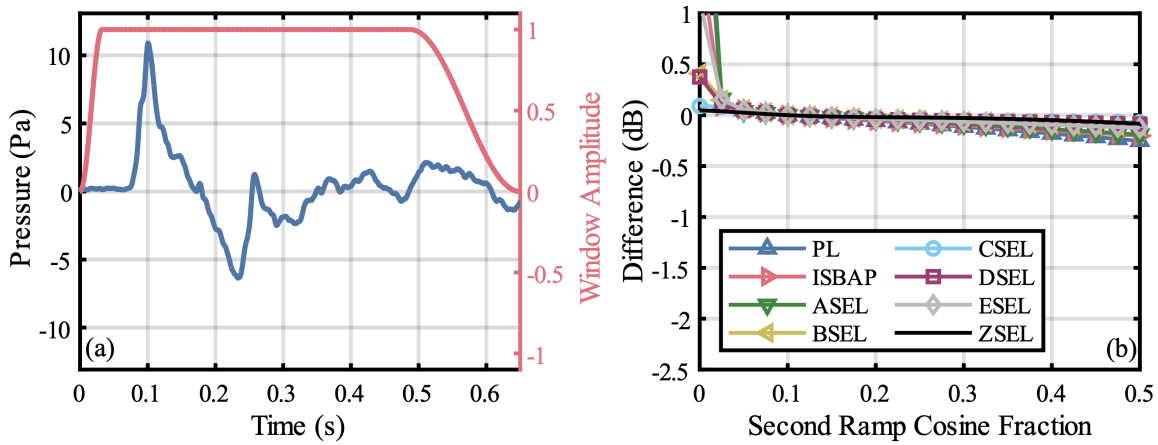


Figure 5.3 Analyzing an asymmetric window on the same boom as analyzed in Fig. 5.2(c) and (d). (a) The boom is shown with an example window. The first ramp has a cosine fraction of 0.1 and the second ramp has a cosine fraction of 0.5, meaning it covers 25% of the recording. (b) The second ramp taper ratio is varied and the effects on the metrics are shown relative to the case where the taper ratio for the second ramp is equal to 0.1.

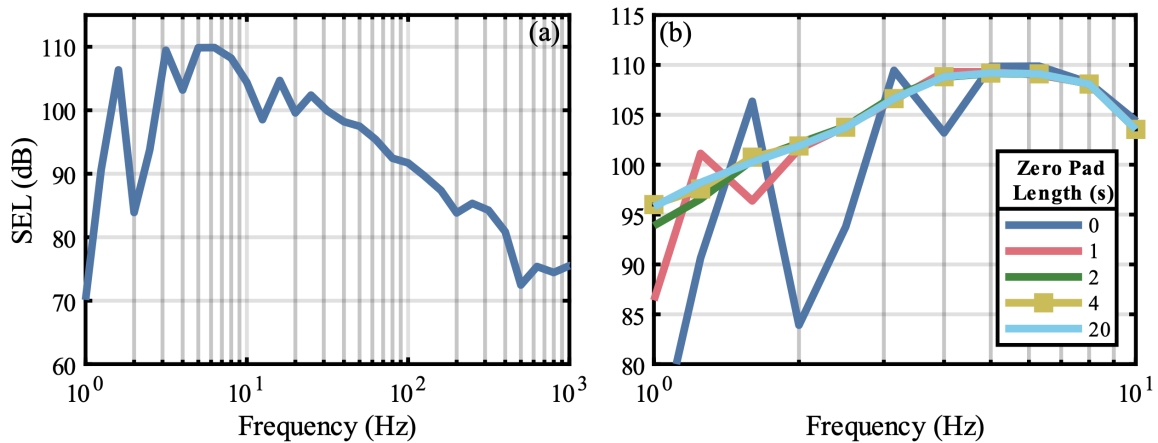


Figure 5.4 Effects of zero-padding. (a) The original OTO spectrum calculated using a 650-ms recording. Notice the jaggedness below 10 Hz. (b) Applying different pad amounts to remove the jaggedness.

5.4 Digital Pole-shift Filtering

Another important choice when making sonic boom measurements is which microphone to use. Sonic booms can have substantial frequency content at low (<10 Hz) and high (>10 kHz) frequencies. Microphones capable of measuring lower frequencies tend to have low sensitivities and thus higher self-noise. This corrupts the high-frequency end of the spectrum and biases some sonic boom

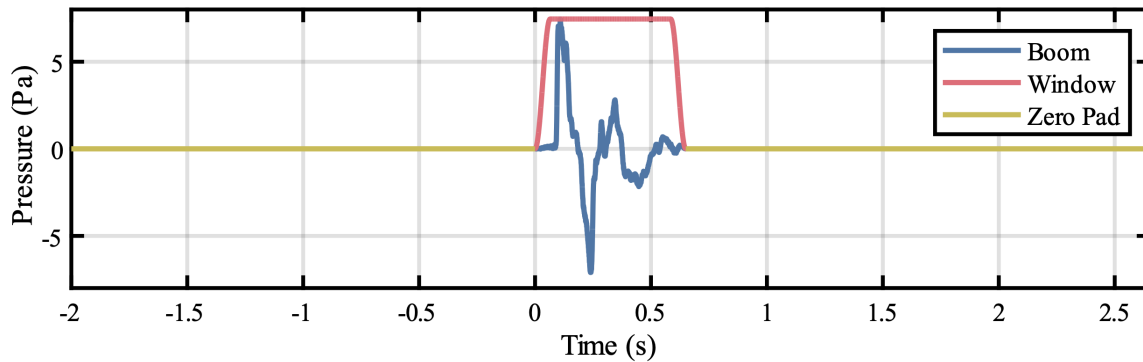


Figure 5.5 An example waveform with the recommended four seconds of zero padding applied to the recording. The pad is applied after windowing, the window height has been scaled to match the waveform amplitude, and the cosine fraction of the window has been increased to 0.2 for easier viewing.

metric calculations. On the other hand, microphones with higher sensitivities, and thus lower self-noise, tend to fail to accurately represent the low-frequency end of the spectrum. This creates a dilemma—we can either use a high-noise microphone to capture the low frequencies properly, or we can use a low-noise microphone to capture the high frequencies properly. The low frequencies are important in accurately representing the waveform shape for comparison with theoretical models, but the higher frequencies are important in calculating the sonic boom metrics (Klos, 2022).

A solution to the problem of poor low-frequency response is to use digital pole-shift filtering (Rasband *et al.*, 2023; Marston, 2008). By shifting the microphone corner frequency to a lower value, this post-processing technique stably adjusts the magnitude and phase of the microphone low-frequency response to account for poor low-frequency performance of higher-sensitivity microphones. Thus, a high-sensitivity, low-self-noise microphone can be used, and the proper waveform shape can still be recovered, satisfying many of the needs of those interested in metrics and those interested in modeling. An example result is shown in Fig. 5.6, which shows measurements of a boom at QSF18 measured with adjacent microphones (Anderson *et al.*, 2022b). Part (a) shows the waveforms. The black curve shows a boom measured with a PCB 378A07 microphone, which represents the target waveform shape because it has the more accurate low-frequency response. A waveform was also measured with a GRAS 40AE microphone (red), a higher-sensitivity microphone with a frequency response that does not resolve the low frequencies. The corrected waveform (green) is the result of applying digital pole-shift filtering to the GRAS 40AE-measured waveform via the methods discussed in (Rasband *et al.*, 2023). Part (a) demonstrates that the corrected waveform is now in much better visual agreement with the PCB 378A07 measurement. Notice from parts (b) and (c) that the corrected result now maintains its lower electrical noise floor at higher frequencies while more accurately capturing the low-frequency content. In short, digital pole-shift filtering can enable accurate waveform representation while still providing low-noise measurements. Customized filters can be applied to better optimize particular hardware configurations, as discussed in Rasband *et al.* (2023).

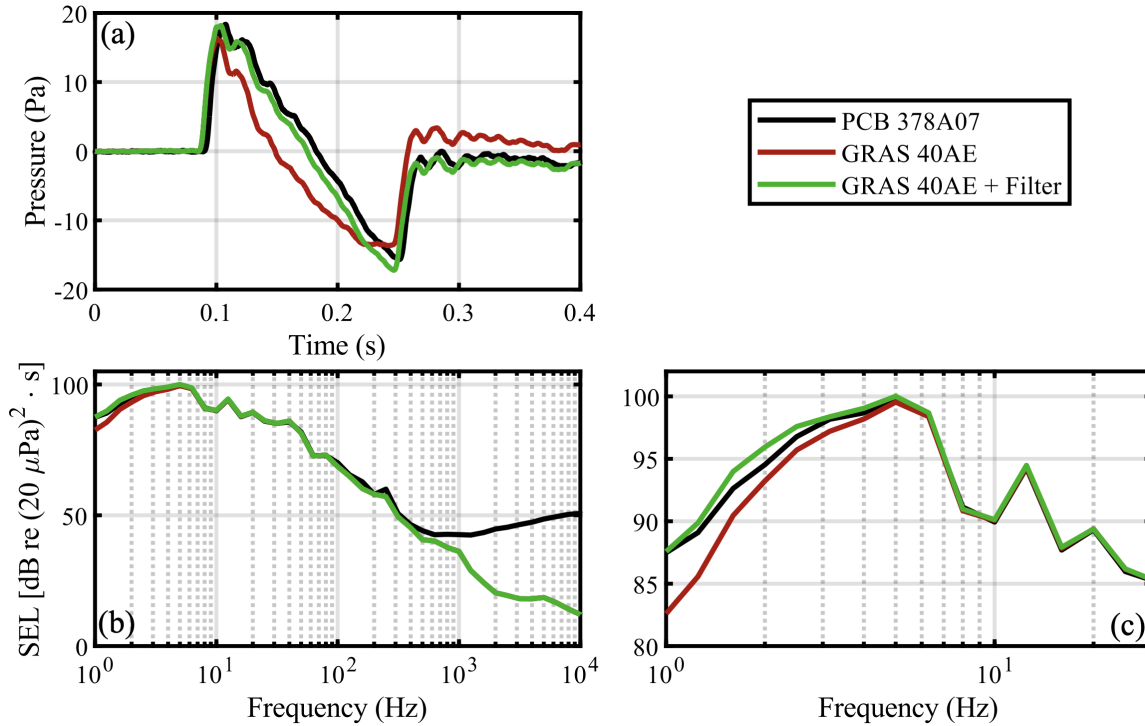


Figure 5.6 Applying digital pole-shift filtering to a measured sonic boom. (a) The GRAS 40AE measurement can be corrected at low frequencies via digital pole-shift filtering to capture the true waveform shape more accurately. (b) Spectra from 1 Hz–10 kHz. Although the PCB 378A07 recording captures the overall waveform shape the best, it has a much higher noise floor than the GRAS 40AE recording. (c) The low-frequency effects of applying the digital pole-shift filter.

5.5 Ground-based vs Elevated Microphones

Elevated microphones have been used in the past as a means of weatherproofing a microphone against water damage (Page *et al.*, 2020; Anderson *et al.*, 2022b). However, elevated microphones are subject to multipath interference at frequencies that are important to sonic boom metrics, as discussed in a recent article by researchers at Volpe Transportation Research Center, BYU, and NASA Langley Research Center (Downs *et al.*, 2022). Some interesting data are shown below that supplement results published by Gee *et al.* (2020), Downs *et al.* (2022), Anderson *et al.* (2022b), and Durrant *et al.* (2022b). The interested reader is referred to those publications for a more thorough treatment of elevated microphones in sonic boom measurements.

Figure 5.7 shows a comparative microphone station at CarpetDIEM I (Durrant *et al.*, 2022b). Three of the channels (with the same type of microphone) are used to produce the results in Fig. 5.8. The three configurations are COUGAR (Anderson *et al.*, 2022a), Ground-Board, and Elevated. Further details on these types of configurations are found in Anderson *et al.* (2022b). Figure 5.8(a)

shows the measured spectra of the three configurations for the same sonic boom. Figure 5.8(b) shows the difference between the mean spectra and the COUGAR configuration over the entire measurement campaign of 22 booms for this location. Notice the strong spectral nulls seen at 400 Hz, 1.25 kHz, and 2 kHz for the Elevated microphone. Figure 5.8(c) shows the loudness spectra in sones for each configuration for the same boom as part (a). Lastly, Fig. 5.8(d) shows the mean loudness spectra over the entire measurement campaign. To better visualize the effects of the Elevated microphone on the mean loudness spectrum, part (d) shows the absolute spectra rather than the relative spectra. The overall loudness reduction effect of elevating a microphone is evident in the reduced spectral levels between 100 and 1000 Hz in the loudness spectra. For the averaged loudness spectra in (d), the COUGAR PL is 101.8 dB, the Ground-Board PL is 102.1 dB, and the Elevated PL is 100.1 dB, meaning that the Elevated setup averaged about 2 dB less for the PL metric than the other two configurations.

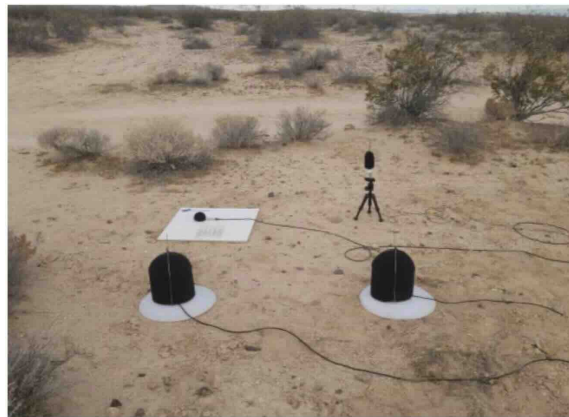


Figure 5.7 Comparative station at CarpetDIEM I. (Top Left) a Ground-Board configuration. (Top Right) An Elevated configuration, with the microphone raised 18 inches (46 cm) above the ground. (Bottom) Two COUGAR configurations with different microphones. The Ground-Board, Elevated, and COUGAR configurations compared in this chapter all use a PCB 378A07 microphone. This station is referred to as PUMA 1 in Durrant *et al.* (2022b).

5.6 Atmospheric Turbulence

Meteorological effects on sonic boom measurements have been studied for decades (Maglieri *et al.*, 2014). Of particular interest is the lowest portion of the atmosphere, known as the atmospheric boundary layer, where turbulence can be much greater than at higher altitudes. Turbulence may cause sonic boom waveforms measured over short distances to vary dramatically. To investigate turbulence effects on sonic booms further, BYU fielded a seven-microphone 400-ft (120-m) linear turbulence array directly under the flight track at CarpetDIEM (Durrant *et al.*, 2022b). The array was oriented perpendicular to the flight track. Figure 5.9 shows the sonic boom from a single flyover

measured at all seven microphones along the array. Notice the large visual differences between the waveforms across the array due to turbulence.

These differences translate into sonic boom metric variability, as indicated in Fig. 5.10(a) for the PL metric. This includes booms from three supersonic overflights (A, B, and C). Each overflight is unique and shows different amounts of variability across the array. When considering the mean metric value for a boom, the confidence interval on that mean value varies with the amount of scatter. For example, Boom A has a narrower confidence interval width than Boom B. Figure 5.10(b) illustrates this for each metric. The metrics across the array for twelve booms at this station were calculated and the confidence interval (CI) half-widths for each metric for each boom were also calculated. The results can be interpreted as follows: the PL 90% confidence interval half-width (i.e., $\text{mean} \pm \text{CI}/2$) was sometimes as narrow as 0.6 dB, but sometimes as wide as 2.7 dB. These results can be compared with those shown by Doeblner (2017), where favorable agreement is found between the two. While these results are all for N-waves, these methods may be useful when studying measurements of low booms. It is therefore recommended that during X-59 testing, similar results be obtained by using multiple microphones at a single location to experimentally determine the variability due to atmospheric turbulence.

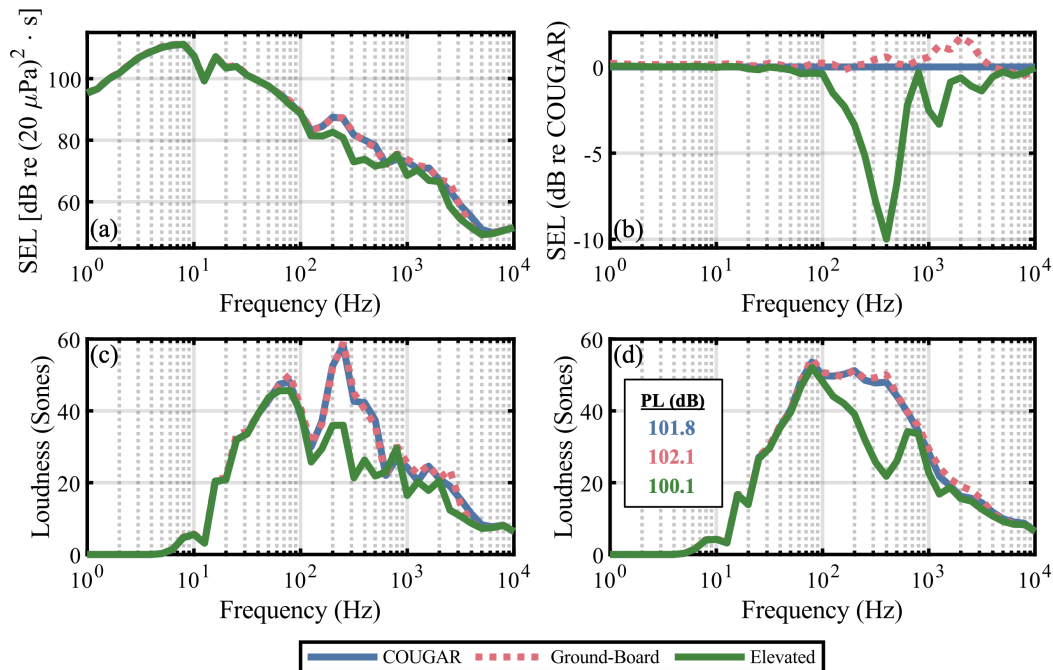


Figure 5.8 Comparison of three different microphone configurations at one location during CarpetDIEM I. (a) Spectra for each channel during a single boom event. (b) Twenty-two measurement mean spectra relative to COUGAR measurements at this location. (c) The loudness spectra for each channel during the same single boom event as part (a). (d) Twenty-two-measurement mean loudness spectra at this station.

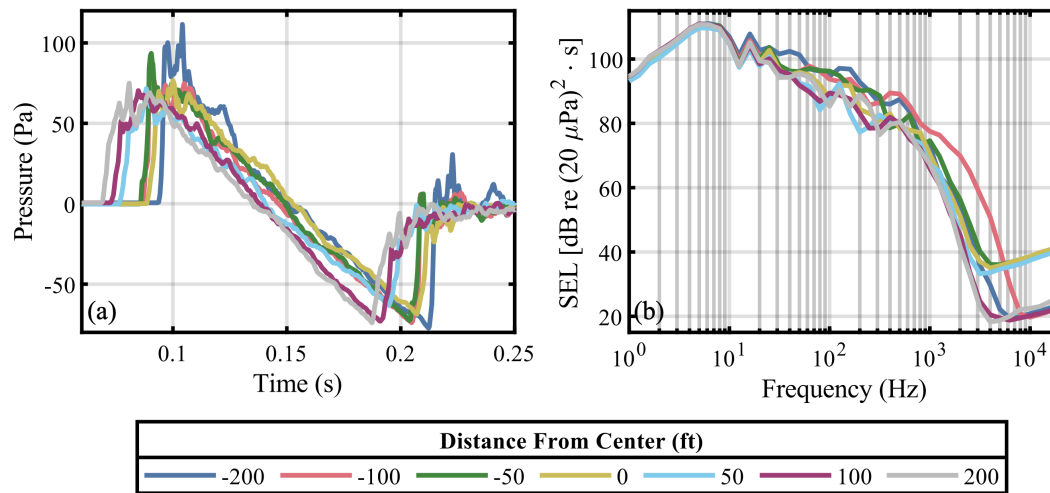


Figure 5.9 (a) Example waveforms measured across the turbulence array for a single boom event. (b) Corresponding spectra for the booms shown in part (a).

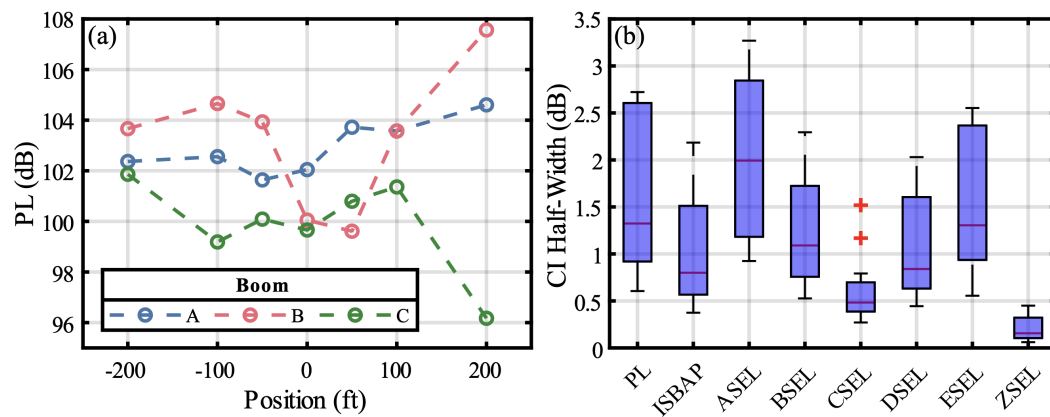


Figure 5.10 The effects of atmospheric turbulence on sonic boom metrics. (a) The PL metric for three example overflights varies widely across the array and each boom is unique. (b) Each overflight ($N=12$) has a unique confidence interval half-width for each metric mean value. Twelve overflights each with 7 boom measurements were used to calculate 90% confidence interval half-widths for each boom for each metric, and the results are shown as a box and whisker plot with the medians shown by a horizontal line. Red plus signs indicate outliers, and the red bars indicate the median values.

5.7 Contaminating Noise Removal

One of the important problems continuing to face outdoor sonic boom measurements is the local ambient and instrumentation noise (Page *et al.*, 2014; Klos, 2020; Anderson *et al.*, 2021; Klos, 2022; Anderson *et al.*, 2024b). Noise can artificially inflate metric values, resulting in an overall bias error in sonic boom metric distributions. To compute accurate sonic boom metrics, this problem must be dealt with effectively.

The following method is proposed for removal of ambient and instrumentation noise (hereafter considered together under the term “contaminating noise”) from sonic boom recordings:

1. Record 650-ms of contaminating noise before the boom, as well as a 650-ms recording containing the boom.
2. Calculate the contaminating noise and the boom spectra, then subtract them to calculate the signal-to-noise ratio (SNR) spectrum.
3. Determine the first OTO band center frequency at which the SNR becomes less than 3 dB. This becomes the filter cutoff or corner frequency.
4. Apply either a sixth-order Butterworth-magnitude filter (time domain) or a brick-wall filter (frequency domain) with the determined cutoff frequency from the previous step. For the brick-wall filter, the spectral data at the cutoff frequency are kept, and data at frequencies greater than the cutoff frequency are removed. Note that the Butterworth filter can be applied as two third-order magnitude filters (one forward and one backward) to produce a usable waveform with zero phase distortion. This can be done in MATLAB® r2022a via the `filtfilt` command.
5. Calculate metrics using the filtered data.

To demonstrate the success of this filtering approach, a detailed example is included in this chapter. For this example, we use a simulated NASA C609 low boom (Rallabhandi and Loubeau, 2022) and real-world contaminating noise recorded during QSF18. The simulated waveform is shown Fig. 5.11(a) and is referred to as the “Clean Boom”. The metrics calculated using this waveform are considered true because there is no contaminating noise. In Fig. 5.11(b), 1300 ms of continuous contaminating noise has been superposed on the clean boom, with 650 ms occurring before the boom recording. The new 1300-ms recording is then split into the “Preboom Contaminating Noise” and the “Mock recording”.

The spectra for these waveforms are shown in Fig. 5.12(a). Notice that the boom spectrum is dominant at low frequencies, and the contaminating noise spectrum is dominant at frequencies greater than a few hundred Hertz. Although there is sometimes contaminating noise due to wind, such effects tend to be at frequencies low enough to have a relatively minor effect on sonic boom metrics. Notice also that the contaminating noise is not stationary, causing the preboom ambient and mock recording spectra not to match perfectly at high frequencies. This effect can also be seen in Fig. 5.12(b), which shows the SNR spectrum of the mock recording relative to the preboom

contaminating noise. This nonstationarity is the reason that a purely spectral-subtraction-based method for contaminating noise removal was avoided when developing this method. Experience tends to show that although the contaminating noise is nonstationary, the method presented in this chapter tends to perform well.

What do the spectra look like after the filtering has been applied? Figure 5.13 contains the filtered mock recording results. Parts (a) and (b) show the flat-weighted spectral results for both the Butterworth and Brick Wall methods respectively. Parts (c) and (d) show the loudness spectra obtained as part of the PL metric calculation. For this example, the clean boom had a PL of 76.1 dB and the mock recording had a PL of 80.1 dB. The Butterworth filter brought the PL down to 76.0 dB and the Brick Wall filter brought the PL down to 75.9 dB. Notice that both types of filters work well and returned the PL to within 0.2 dB of the clean case. Note also that because the Brick Wall filter performed similarly to the Butterworth filter, we can conclude that attempts to match the high-frequency spectral slope of the clean boom more closely are unlikely to yield large improvements. It is also important to note that this method, like other methods such as the methods proposed by Klos (2022), relies on the assumption that the contaminating noise is stationary. Additional limitations of the methods proposed in this chapter are that tonal noise can cause the filter cutoff frequency to be set to an unnecessarily low frequency and that results are limited to low-pass filtering.

How does this approach compare to another state-of-the-art technique? Klos (2022) proposed an adaptation of ISO 11204 (ISO11204:2010, 2010) that allows for more aggressive corrections than typically afforded by that standard. The most successful of the proposed adaptations are denoted “Custom E” and “Custom F” To make a direct comparison, a set of 300 simulated C609 low booms

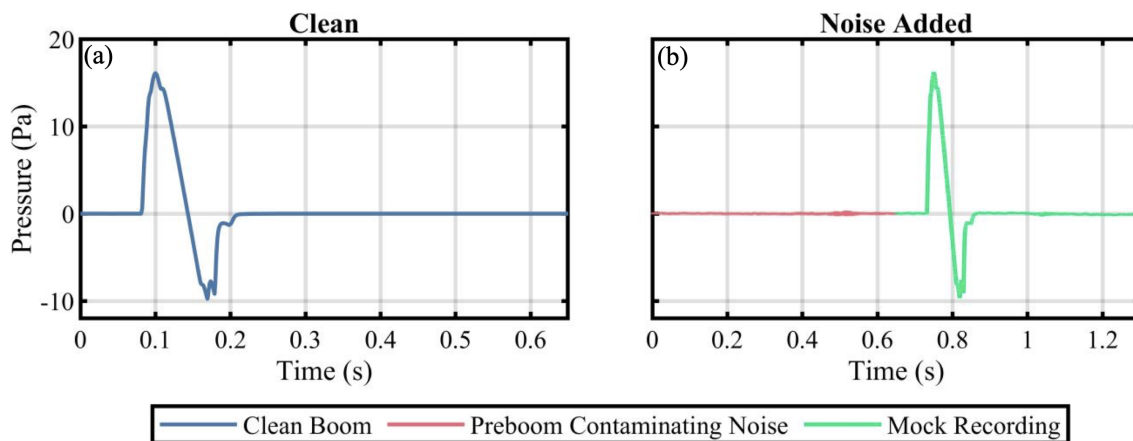


Figure 5.11 (a) A simulated low boom, known as the clean boom. (b) A total of 1300 ms of contaminating noise has been superposed on the clean boom, with 650 ms being placed before the start of the boom portion of the recording. The new waveform is 1300 ms in duration and can be split into a preboom contaminating noise phase and a mock recording phase.

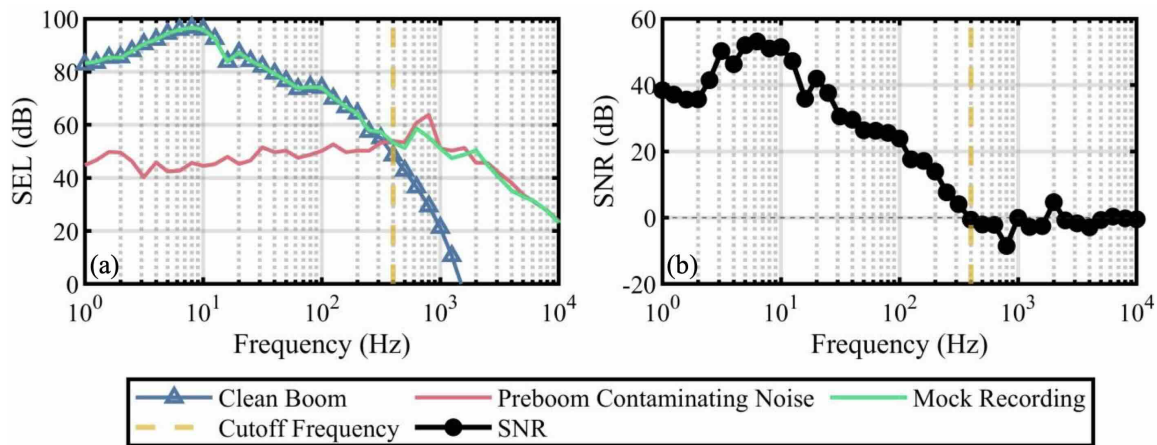


Figure 5.12 Determining the cutoff frequency. (a) The three spectra are plotted together. (b) The SNR between the Mock Recording and the Preboom Contaminating Noise.

were randomly paired with contaminating noise recordings from QSF18. The differences between the filtered mock recording PL values and the clean boom PL values were calculated and are shown as histograms in Fig. 5.13. Part (a) shows only the results using the ISO 11204 adaptations. Part (b) superimposes the results from the methods proposed in this chapter. All four methods successfully remove the contaminating noise for the PL metric. These methods should all continue to be studied once real low-boom measurements are available. It is possible that multiple methods ought to be used in tandem because they are likely robust to different types of errors.

Further details on the methods proposed within this chapter have been recently published in the *Journal of the Acoustical Society of America* (Anderson *et al.*, 2024b).

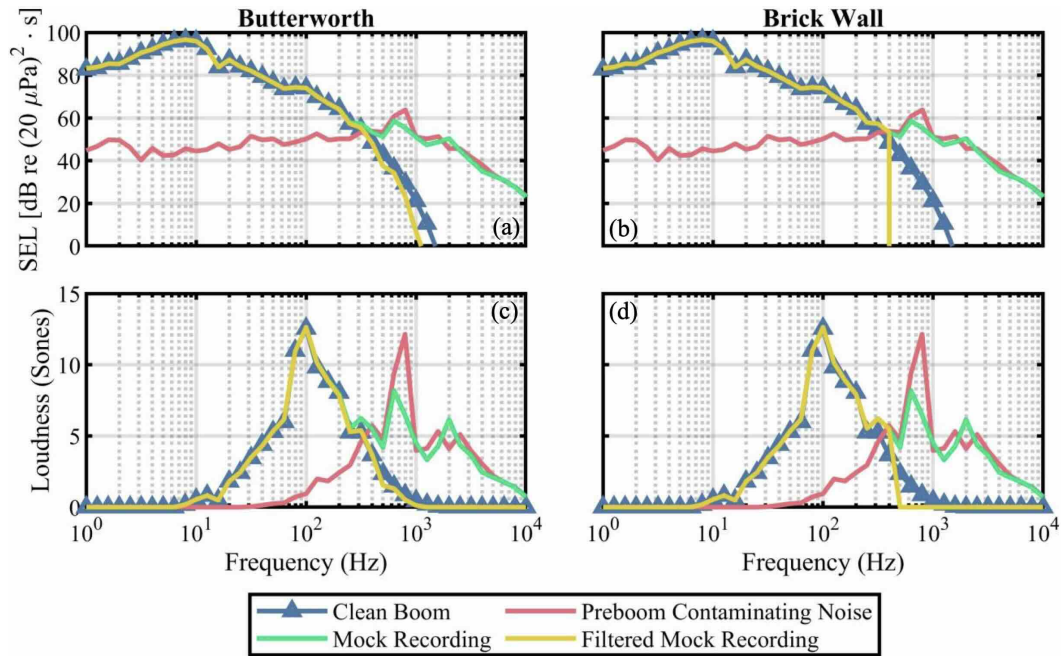


Figure 5.13 Applying the filters to the data: (a) the flat-weighted spectra using the Butterworth filter, (b) the flat-weighted spectra using the Brick Wall filter, (c) the loudness spectra using the Butterworth filter, and (d) the loudness spectra using the Brick Wall filter.

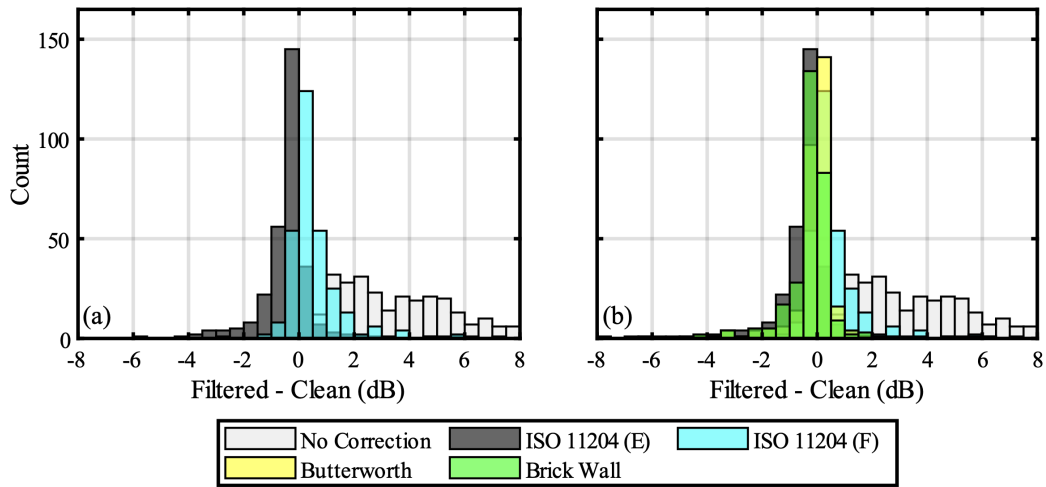


Figure 5.14 Comparison with the method proposed in Klos (2022): (a) the distribution of filtered metrics relative to the clean boom and (b) the same distributions, but with the filtering methods proposed in this chapter included. Note that the “No Correction” case extends beyond the plot limits up to a maximum value of +20.6 dB.

5.8 Summary of Recommendations

The methods outlined and summarized in this chapter have primarily focused on how to make accurate sonic boom measurements and how to process the recordings to obtain high-fidelity results. This research has spanned several topics, and the current recommendations are given in this chapter. In summary, we recommend:

- Use a Tukey (tapered-cosine) window for time-domain windowing prior to an FFT analysis. Ensure that the taper does not impact the primary shock.
- Use up to four seconds of zero padding for smooth spectra down to 1 Hz when performing an FFT-based OTO spectral analysis and the recording length is 650 ms.
- Use a high-sensitivity microphone that will accurately capture the higher frequencies. To restore the low-frequency content, apply digital pole-shift filtering.
- Use weather-robust ground-based microphones instead of elevated microphones.
- Use multiple microphones at a recording station during X-59 measurements to experimentally determine variability due to atmospheric turbulence.
- Use a sixth-order Butterworth magnitude filter to remove ambient and instrumentation noise from recordings. Alternatively, a frequency-domain Brick Wall filter may also be used, or those methods proposed by Klos (2022). These methods should all be used in tandem to produce error bars on final results.

Further recommendations regarding these topics can be found in the references included herein as well as within a published NASA contractor report (Gee *et al.*, 2024a).

Acknowledgements

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Part II

Rocket Booster Flyback Sonic Booms

Chapter 6

Comparing the Flyback Sonic Boom to Other Launch-related Noise

Abstract

¹For the past several years, Space Exploration Technologies Corporation (SpaceX) has been propulsively landing first stage rocket boosters for reuse. Because the boosters return at supersonic speeds, they produce a sonic boom. As the landing cadence continues to increase, it is important to understand these sonic booms and how they propagate to the surrounding areas. This chapter reports on measurements made of the SpaceX Transporter-8 launch and landing of a Falcon-9 rocket at Vandenberg Space Force Base. A unique triple-boom shape is preserved over propagation distances as close as 300 m and as far as 25 km from the landing pad. At distances greater than about 1 km, the sonic boom peak overpressure exceeds the launch peak pressure. Additionally, sound exposure metrics indicate that the sonic boom itself is comparable to the rest of the launch noise. Conclusions from these results include that sonic booms should be considered alongside launch noise when considering sound exposure and that there remain several mysteries regarding the propagation of these unique triple booms.

¹This chapter is derived from a paper published in the conference proceedings of the American Institute of Aeronautics and Astronautics with the following citation:

Anderson, M. C., and Gee, K. L. (2024). “Sonic boom measurements from the SpaceX Transporter-8 Falcon-9 rocket landing at Vandenberg Space Force Base,” in 30th AIAA/CEAS Aeroacoustics Conference. <https://doi.org/10.2514/6.2024-3188>

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6.1 Introduction

Commercial space operations have been growing rapidly over the past several years, with the emergence of many new competitors in this market. To decrease costs, an important aspect of the modern commercial space industry is the drive towards rocket reusability. While SpaceX is the first commercial company to successfully relaunch an orbital-class rocket booster, many other companies are working on developing reusable orbital-class rockets. This includes RocketLab, Blue Origin, Relativity Space, and Stoke Space, to name a few. The most common reuse strategy is to propulsively land the rocket either in full or in part on a barge in the ocean or on a land-based platform. The land-based approach is particularly appealing because it reduces overall costs by eliminating the need for ocean-based vessels in the recovery efforts.

When a rocket falls through the atmosphere at supersonic speeds, it produces a sonic boom as a result of shock waves forming along the body of the rocket and then propagating to great distances (Durrant *et al.*, 2022a, 2023; Whitham, 1952). Although sonic booms have been extensively researched for decades (Maglieri *et al.*, 2014), including sonic booms from the Space Shuttle reentry (Maglieri *et al.*, 2011), the sonic booms produced by vertically-landing rockets are unique and have only been lightly touched upon in the scientific literature (Durrant *et al.*, 2022a, 2023).

One reason the study of rocket landing sonic booms is important is to determine the acoustical environments the surrounding facilities, wildlife, and communities are subjected to during a launch and landing. Using a SpaceX Falcon-9 launch and landing, Durrant *et al.* (2023) found that at observer distances greater than about 1 km, the sonic boom represented the highest pressure event of the entire flight. At farther distances, it was found that the sonic boom A-weighted sound exposure level (ASEL) over 650 ms was only 2 dB below the ASEL integrated over the 31 highest-pressure seconds of the launch noise at 8.4 km. Thus, the sonic boom represents a substantial noise source.

Current modeling approaches to rocket landing sonic booms are limited and relatively little is known regarding exact methods for making predictions. In 2020, a report covering several years of studies was released by the Federal Aviation Administration (FAA) detailing environmental effects from the SpaceX Falcon family of rockets (FAA, 2020a). This report contains an appendix dedicated to launch noise and sonic boom studies. Within this appendix is a brief overview of the SpaceX modeling methods for the sonic boom peak overpressures. They found in 2015 that NASA's PCBoom software (Page *et al.*, 2023) tended to underpredict peak overpressures unless detailed atmospheric models were used. To simplify their modeling approach, they ultimately used an adapted form of the NASA 1122 simplified sonic boom prediction method (Carlson, 1978). This method was adapted to produce results that agreed with measurements. While tailoring a model to match a specific vehicle may produce accurate results for that particular vehicle, it produces a model with only limited usefulness. This type of model may be more empirical than physical, meaning that it cannot be confidently ported over to other launch vehicles or abnormal weather conditions. A 2021 report indicates that SpaceX plans to follow a similar methodology for the Starship vehicle (Bradley *et al.*, 2021), using measured data to tailor the NASA 1122 methods to their vehicle. Until measured data are available, generic predictions are being created using the Space Shuttle Orbiter parameters in PCBoom.

The NASA 1122 modeling approach has further, more fundamental, issues when being applied to the Falcon family of rockets. A characteristic feature of rocket landings from the Falcon family is a unique triple boom signature (Durrant *et al.*, 2022a, 2023) that is audible all the way into the surrounding communities (Johnson, 2016). This type of signature is not predictable using the original NASA 1122 method, in which one must include “the assumption that the pressure signal generated by the aircraft is of the far-field type, the classical N-wave” (Carlson, 1978). It is unclear whether this issue has been overcome, as there are no predicted waveforms in the FAA reports.

The purpose of this chapter is to provide measured data from a Falcon-9 sonic boom measurement and represents a preliminary analysis. Several important topics for future research will be introduced and briefly discussed. The remainder of this chapter proceeds as follows: Section 6.2 details the measurement campaign that supplies the data for this analysis. Sections 6.3 and 6.4 detail the measured sonic boom properties in the time and frequency domains respectively. Section 6.5 provides a comparison between the launch, sonic boom, and landing noise and, lastly, Section 6.6 highlights the key results of these analyses.

6.2 Measurements

The SpaceX Transporter-8 mission lifted off from Vandenberg Space Force Base at 2:35 PM local time on June 12, 2023 (SpaceX, 2023). The Falcon-9 launch vehicle traveled south before the first-stage booster shut down and separated from the upper stage at about 65 km above the ground, per video telemetry. Following separation, the booster performed a flip maneuver and ignited its engines again to travel back to the landing pad, located adjacent to the launch pad. Falling from an apogee of 132 km and maximum speed of about 1300 m/s, per video telemetry, the booster guided itself safely onto the landing pad. A sonic boom was heard over the surrounding area, reaching distances of at least 25 km. Overall, the booster’s entire flight lasted less than eight minutes.

During this launch and landing, Brigham Young University (BYU), in collaboration with California State University at Bakersfield (CSUB) successfully fielded 13 measurement stations surrounding the launch and landing pads, as shown below in Fig. 6.1. These stations ranged in distances of 290 m – 25 km from the landing pad and covered a wide variety of headings relative to the landing pad. The stations at closer distances enable a detailed analysis of the environment near the launch and landing pads, where the sound levels from the launch and landing are the highest. The stations at farther distances enable an improved understanding of what communities and wildlife farther from the launch site experience during a launch and landing. The specific hardware used is detailed in Table 6.1. Out of 22 measurement setups, a few were duplicates at the same locations and some experienced peak-pressure clipping during the sonic boom portion of the measurement, as the hardware had been optimized for the launch noise. The 13 unique stations that did not experience clipping are included in this table.

Overall, this measurement was similar to other recent rocket launch and sonic boom measurements conducted by BYU in collaboration with CSUB (Durrant *et al.*, 2023; Cunningham *et al.*, 2023; Mathews *et al.*, 2023). An example measurement station is shown in Fig. 6.2. Microphones were inverted above plastic ground plates and shrouded beneath a dome windscreen, a microphone

configuration that was specifically designed for both rocket launch and sonic boom measurements (James *et al.*, 2020a; Anderson *et al.*, 2022a). To account for the rapid low-frequency rolloff of some hardware components, digital pole-shift filtering was applied to boost those low-frequency components and restore the waveform shape (Marston, 2008; Rasband *et al.*, 2023).

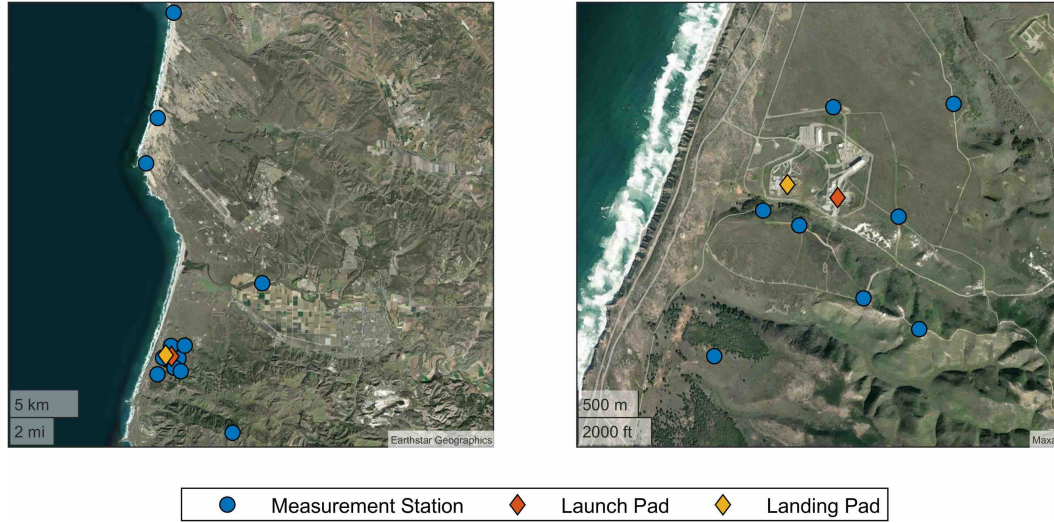


Figure 6.1 Maps of the measurement locations, the launch pad, and the landing pad. (Left) A view showing all 13 measurement stations. Imagery credit: Earthstar Geographics. (Right) Zoomed in view showing the closer stations in more detail. Imagery credit: Maxar.

Table 6.1 The different hardware used at each measurement station along with details regarding the location of each station. In this table, “LD” is short for Larson Davis.

Station Number	Distance To Launch Pad (m)	Distance To Landing Pad (m)	Microphone	DAQ Card	Latitude (°N)	Longitude (°W)
1	530	960	GRAS 46BD	NI 9250	34.630650	-120.605136
2	390	340	GRAS 46BD	NI 9250	34.630000	-120.614100
3	630	290	GRAS 46BD	NI 9250	34.631097	-120.617358
4	750	740	GRAS 46BE	NI 9250	34.638761	-120.611028
5	860	1100	GRAS 46BE	NI 9250	34.624600	-120.608300
6	1200	1500	GRAS 47AC	NI 9250	34.639003	-120.600158
7	1300	1600	GRAS 47AC	NI 9250	34.622314	-120.603269
8	1700	1500	GRAS 47AC	NI 9250	34.620314	-120.621778
13	14000	14000	GRAS 46AE	NI 9234	34.757606	-120.630775
15	8400	8700	GRAS 46AE	NI 9234	34.679600	-120.538600
20	17000	17000	PCB 377B02	LD 831-C	34.787053	-120.621531
21	25000	25000	PCB 377B02	LD 831-C	34.855465	-120.608929
22	7100	7500	PCB 377B02	LD 831-C	34.582262	-120.562217



Figure 6.2 Example measurement setup near the launch pad. Although this station had four microphones, most stations used a single microphone.

6.3 Time Domain Sonic Boom Properties

A unique property of the sonic booms produced by Falcon-9 boosters during landings is the presence of at least three distinct shocks. Several measured waveforms from the Transporter-8 booster landing are shown in Fig. 6.3. These measurements were obtained at different distances from the landing pad, but all contain the unique “triple boom” shape. This may be an example of sonic boom freezing (McLean, 1965; Hayes, 1967; Hayes *et al.*, 1968), especially because the booms may be generated at higher altitude than most other sonic booms (Cleveland and Blackstock, 1996).

The overall waveform shape remains strikingly consistent at different measurement locations. Figure 6.4(a) compares the waveform shapes between the nearest (290 m) and farthest (25 km) measurements. The amplitudes have both been scaled to enable easier visual comparison. The three primary shocks are found in precisely the same relative locations within the waveform. This result is surprising because sonic boom signatures typically elongate with increased propagation distance (Whitham, 1952; Carlson, 1978). It is possible that this unique effect could be due to a combination of waveform freezing (McLean, 1965; Hayes, 1967; Hayes *et al.*, 1968), vehicle trajectory, Mach number, or other as-yet-unknown effects.

While the locations of the shocks are nearly identical in the nearest and farthest measurements, their rise times are not. This is illustrated in Fig. 6.4(b), where the first shock is shown for both of the waveforms. Because many of the waveforms acquired during this measurement have peak pressures that come after the primary shock, the notion of rise time is difficult to define. This is noticeable for the boom measured at 290 m, where the primary shock is only about 80% of the peak pressure. A temporary solution to this problem is to determine the rise times by manually inspecting

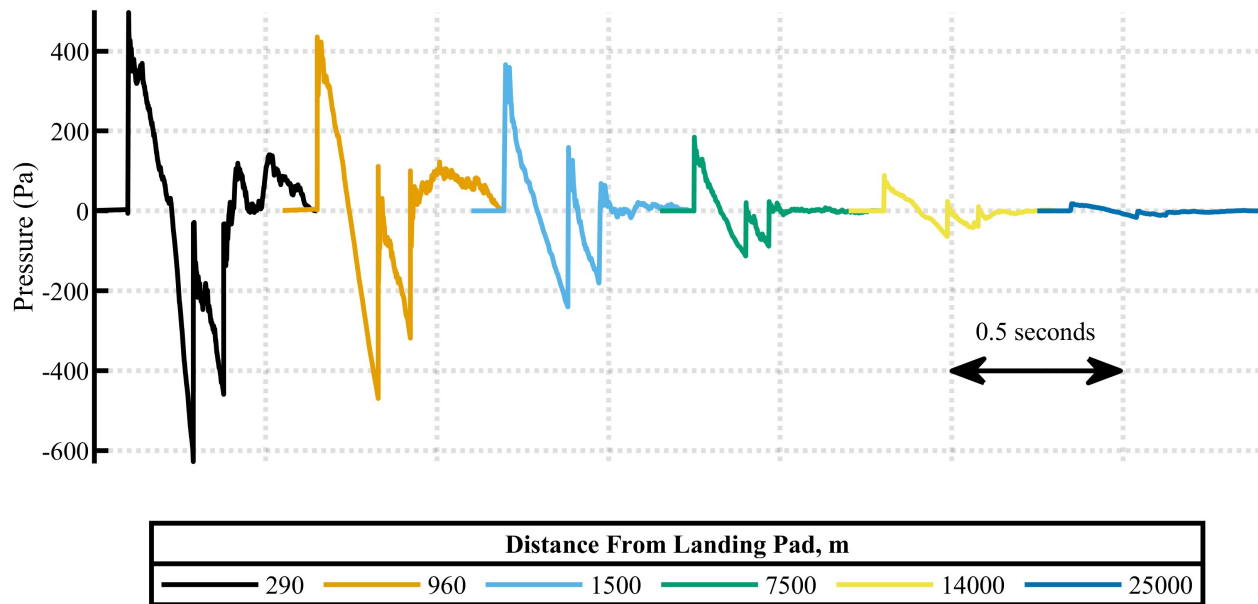


Figure 6.3 Sonic boom waveforms measured at different distances from the landing pad. Waveform separation is arbitrary.

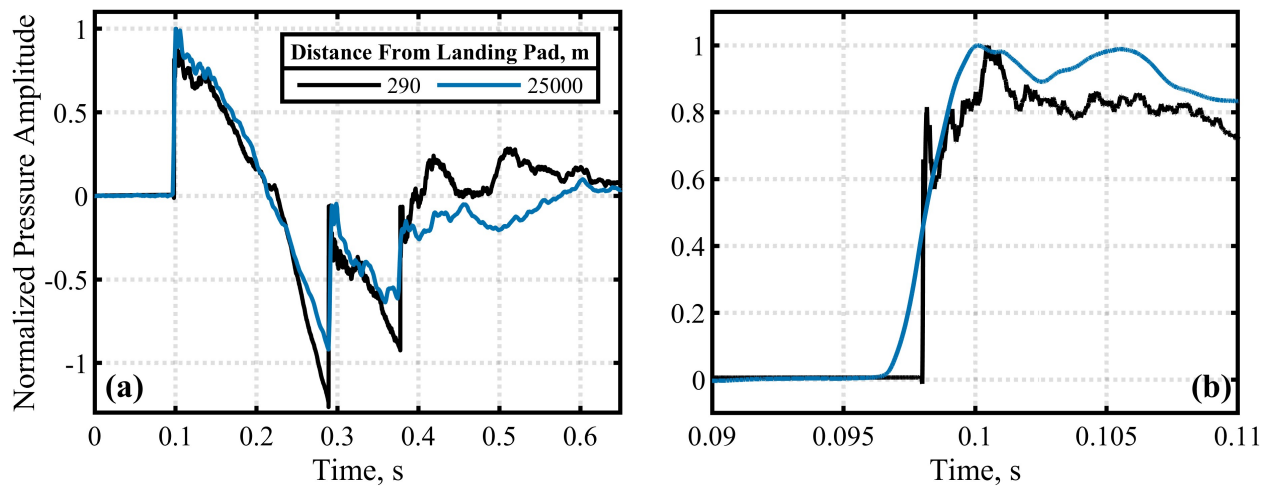


Figure 6.4 Comparison of the nearest and farthest sonic boom measurements. The waveforms have been scaled to a maximum positive amplitude of unity.

the waveforms and determining the duration of the shock from initial shock onset to the peak of the shock, which in general was different from the overall waveform peak. Using this technique, the 290-m measurement had a rise time of 0.039 ms and the 25 km measurement had a rise time of 3.6 ms, approximately a factor of one hundred difference between the two.

The rise times can similarly be calculated for all measured booms to determine a trend with distance. The results are shown in Fig. 6.5, where subplot (a) shows the rise time versus distance from the landing pad and subplot (b) plots the same data on a map of the surrounding area. As the distance from the landing pad increases, there is a clear upward trend in the rise time, as expected from atmospheric absorption effects on shock waves (Hamilton and Blackstock, 2024).

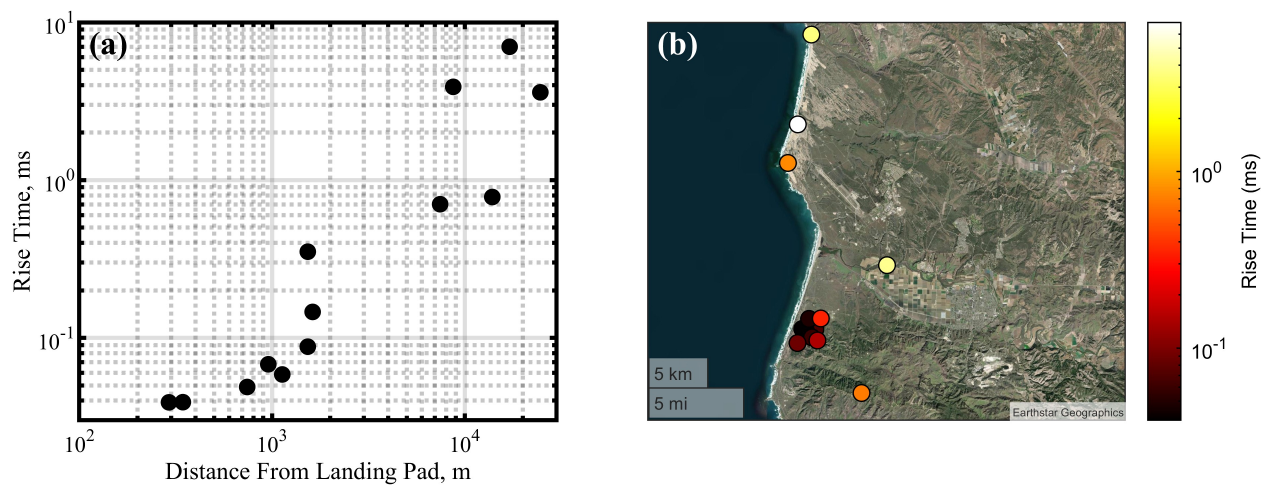


Figure 6.5 Rise time comparison with distance. (a) each station’s rise time compared graphically. (b) Visualization of the different rise times throughout the surrounding area.

It is also noteworthy that the rise time appears to plateau at closer distances. There is a potential explanation for this phenomenon. The descending booster becomes subsonic a few kilometers above the landing pad, per video telemetry (SpaceX, 2023). Therefore, the rays that reach the closest stations to the landing pad are emitted downward while the vehicle is still a few kilometers in the air. This results in the booms measured at the closer stations having all propagated a similar distance and they would have similar properties. This is investigated for other metrics in Sec. 6.5.

6.4 Frequency-Domain Sonic Boom Properties

The frequency content of the Falcon-9 sonic booms is also of both practical and scientific interest. Sample spectra from the Transporter-8 flyback sonic boom are shown in Fig. 6.6. The colors correspond to the waveforms shown in Fig. 6.3, where the recording time was 650 ms, which has been used in the past for aircraft sonic booms (Page *et al.*, 2014). Almost all the spectra peak at about 2.5 Hz, excepting the station at 7500 m, which had a sonic boom with a slightly shorter

duration than the others and thus a higher peak frequency. Understanding the peak frequency is important for modeling the effects on observers inside structures (Loubeau and Page, 2018).

The high-frequency spectral slope is useful for understanding the shock waves contained in the sonic boom recordings. The stations closer to the pad (290 m and 960 m) closely follow the ideal shock decay of $1/f^2$, where f is the frequency. This ideal slope is indicated by the dashed line in Fig. 6.6. Farther stations also follow this ideal slope over a range of frequencies, but then begin to decay faster at higher frequencies. The stations located at 14 and 25 km have noticeable “knees” in the spectra. This transition frequency is expected to be related to the shock rise time (Hamilton and Blackstock, 2024).

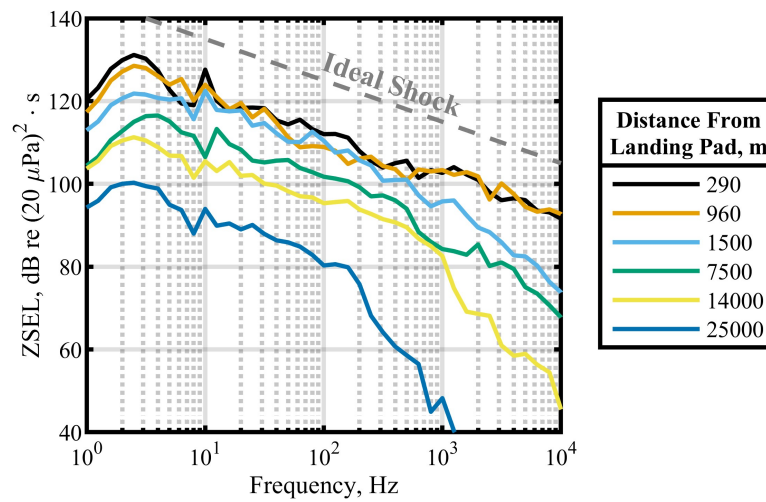


Figure 6.6 Comparison of one-third octave band spectra at different distances from the landing pad. The high-frequency rolloff for an ideal shock is indicated. These stations are the same as those shown in Fig. 6.3.

6.5 Comparison with Launch Noise

6.5.1 Metrics

To simplify sonic boom human annoyance estimates, NASA has developed a set of metrics that are calculated for sonic booms from traditional aircraft. This includes the A-, B-, D-, and E-weighted sound exposure levels (SEL), a modified version (Shepherd and Sullivan, 1991) of the Stevens Mark VII Perceived Level of Loudness (PL) Stevens (1972), and the Indoor Sonic Boom Annoyance Predictor (ISBAP) (Loubeau *et al.*, 2015; Loubeau and Page, 2018). Because the modified PL and the ISBAP metrics contain assumptions that are sonic-boom specific, these two metrics are omitted from the following comparisons with launch and landing noise.

The sonic boom provides substantial sound exposure and ought to be considered alongside the other noise sources including the primary launch noise and the post-sonic-boom noise generated

by the propulsive landing. The different NASA-selected SEL weightings, along with C- and Z-weighting, are shown for each station in Fig. 6.7. To produce these results, the launch and landing noise portions of the recordings were integrated over the 12 dB-down periods to ensure that the majority of the sound energy was captured while limiting the amount of instrumentation noise that might corrupt the higher frequencies late into the launch. Note that the launch noise points are shown relative to the launch pad while the sonic boom and landing noise points are shown relative to the landing pad.

The decay rate with distances from the pad is different for the sonic boom when compared against the launch and landing noise. Both the launch and landing noise sound exposure levels tend to decrease smoothly with distance at a near-constant rate. The sonic boom remains relatively constant out to a distance of around 2 km before transitioning to the same decay rate as the other noise sources. It is hypothesized that the stations closest to the pad are all approximately equidistant from the sonic boom source, which was generated no lower than about 3 km above the landing pad according to when the booster becomes subsonic on reentry.

Because most observers and portions of the infrastructure around a launch site will be greater than 2 km away from the landing site, it is relevant to consider the farther stations. For each SEL weighting, the sonic boom tends to lie between the landing noise and launch noise at distances greater than 6 km from the pad. At these distances, the 12 dB-down period for the launch noise generally lasted between 40–100 seconds and the 12 dB-down period for the landing noise generally lasted between 10–20 seconds. In 650 ms, the sonic boom can yield more sound exposure than 10–20 seconds of landing noise and sometimes nearly as much as 40–100 seconds of launch noise.

When considering the peak overpressure, the sonic boom tends to dominate all other launch and landing noise sources except near the pad. The peak pressures for the launch, sonic boom, and landing noise are plotted together as a function of distance in Fig. 6.8. While the launch noise has the highest peak overpressure near the pad, the sonic boom becomes the dominant overpressure event of the entire flight at distances greater than 1–2 km. This agrees well with the results from Durrant *et al.* (2023). Near the pad, the landing noise and sonic boom peak pressures are similar, but at farther distances the sonic boom has a peak overpressure that is a full order of magnitude greater than the landing noise.

6.5.2 Spectra

The sonic boom does not contain the same spectral content as the launch and landing noise. Rather, the sonic boom has a peak frequency that is an entire order of magnitude lower than the launch noise, as illustrated in Fig. 6.9. This figure shows the flat-weighted sound exposure level spectra, corresponding to the recordings used in Fig. 6.3, alongside the launch and landing noise that was measured at each respective measurement location. As in Fig. 6.7, the launch and landing noise have been integrated over the 12 dB-down periods to maximize the energy captured while minimizing high-frequency instrumentation noise buildup during the integration.

Noted in the legend for each sub-plot in Fig. 6.9 is the duration of each recording that was used to produce the spectra. While it may not be surprising that the launch noise sound exposure is more than the sonic boom, it is impressive that the sonic boom can yield a comparable amount

of energy in 650 ms to the entire 12 dB-down period of the launch. This is especially true at the farther measurement locations, which is also where observers are most likely to be. This further strengthens the argument that the sonic boom sound exposure at distances where people will be is at least as important to consider as the primary launch noise.

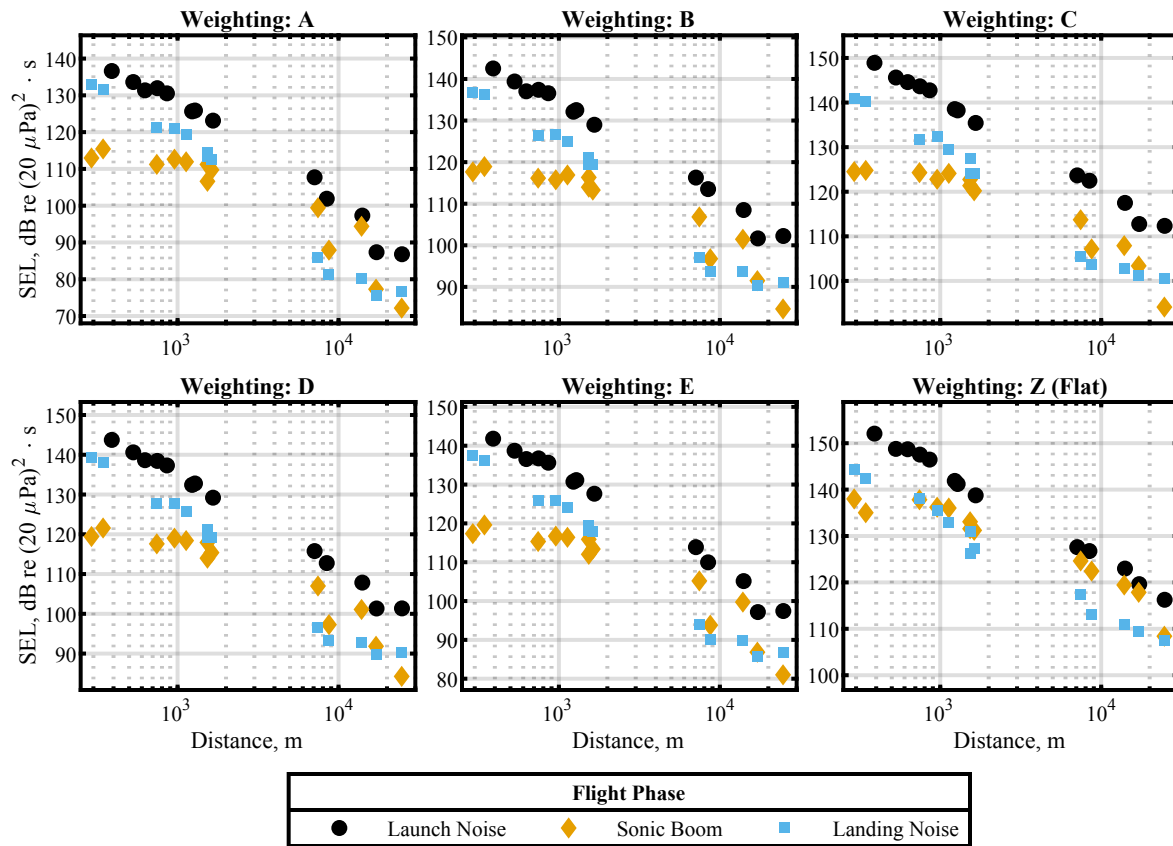


Figure 6.7 Different sound exposure level (SEL) weightings. The launch and landing noise were integrated over the 12 dB-down periods while each sonic boom used a 650-ms recording. The launch noise distances are relative to the launch pad and the sonic boom and landing noise distances are relative to the landing pad. The decibel reference for each plot is $(20 \mu\text{Pa})^2 \cdot \text{sec}$.

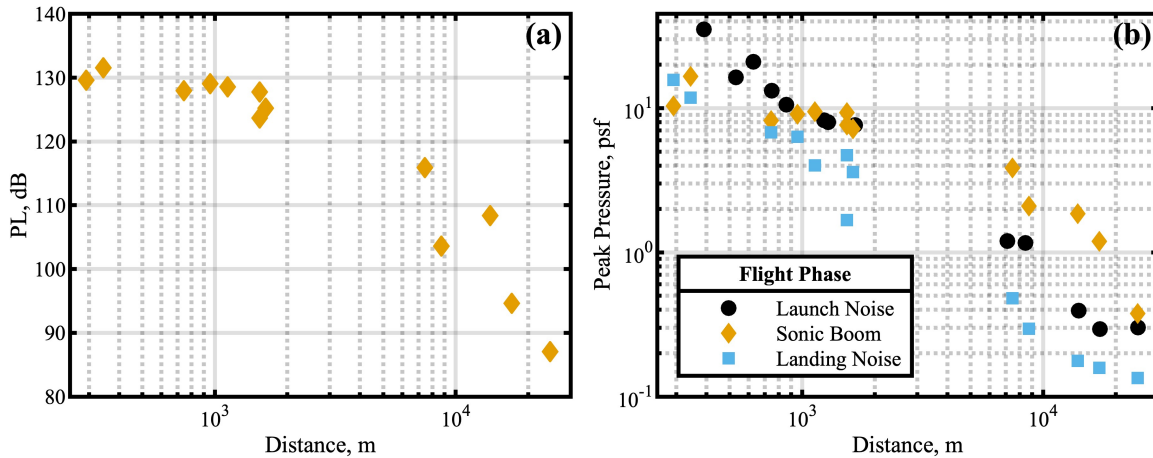


Figure 6.8 (a) The sonic boom PL as a function of distance from the landing pad. (b) The peak pressures as a function of distance for each phase of the flight. The launch noise distances are relative to the launch pad and the sonic boom and landing noise distances are relative to the landing pad.

6.6 Conclusion

Measurements of the SpaceX Transporter-8 Falcon-9 launch and landing enable an analysis of the sonic boom noise and comparisons with other launch and landing noise sources. There were 13 measurement stations located between 290 m – 25 km from the landing pad. All measurements indicate that the sonic boom represents a substantial noise source that ought to be studied further as rockets continue to land more often in the coming years.

Each measuring station recorded a sonic boom signature with three primary shocks. Considering that the farthest measurement station was located 25 km from the landing pad, it is surprising that the signature did not coalesce into a traditional N-wave. A further peculiarity with these measurements is that the nearest and farthest measured waveforms have the same durations and have all three shocks located in the same locations within the waveforms, whereas it would typically be expected that the farther measurement should have an elongated signature.

The sonic boom spectra indicate a peak frequency that is typically around 2.5 Hz. Above this frequency, the spectra typically have a $1/f^2$ rolloff that corresponds to shock-like behavior. At the farther distances, this rolloff transitions to an exponential decay rate at a frequency that should compare favorably with the shock rise times.

The total sound exposure from the sonic boom is non-negligible compared to the rest of the launch and landing noise. At distances greater than a few kilometers, the sonic boom sound exposure dominates the sound exposure from the landing burn noise. Depending on the frequency weighting used, the sonic boom sound exposure approaches the sound exposure from the primary launch noise at some of these same distances. This is remarkable considering that the sonic boom sound exposure was calculated over a 650-ms interval, compared to the 40–100 seconds used for the launch noise.

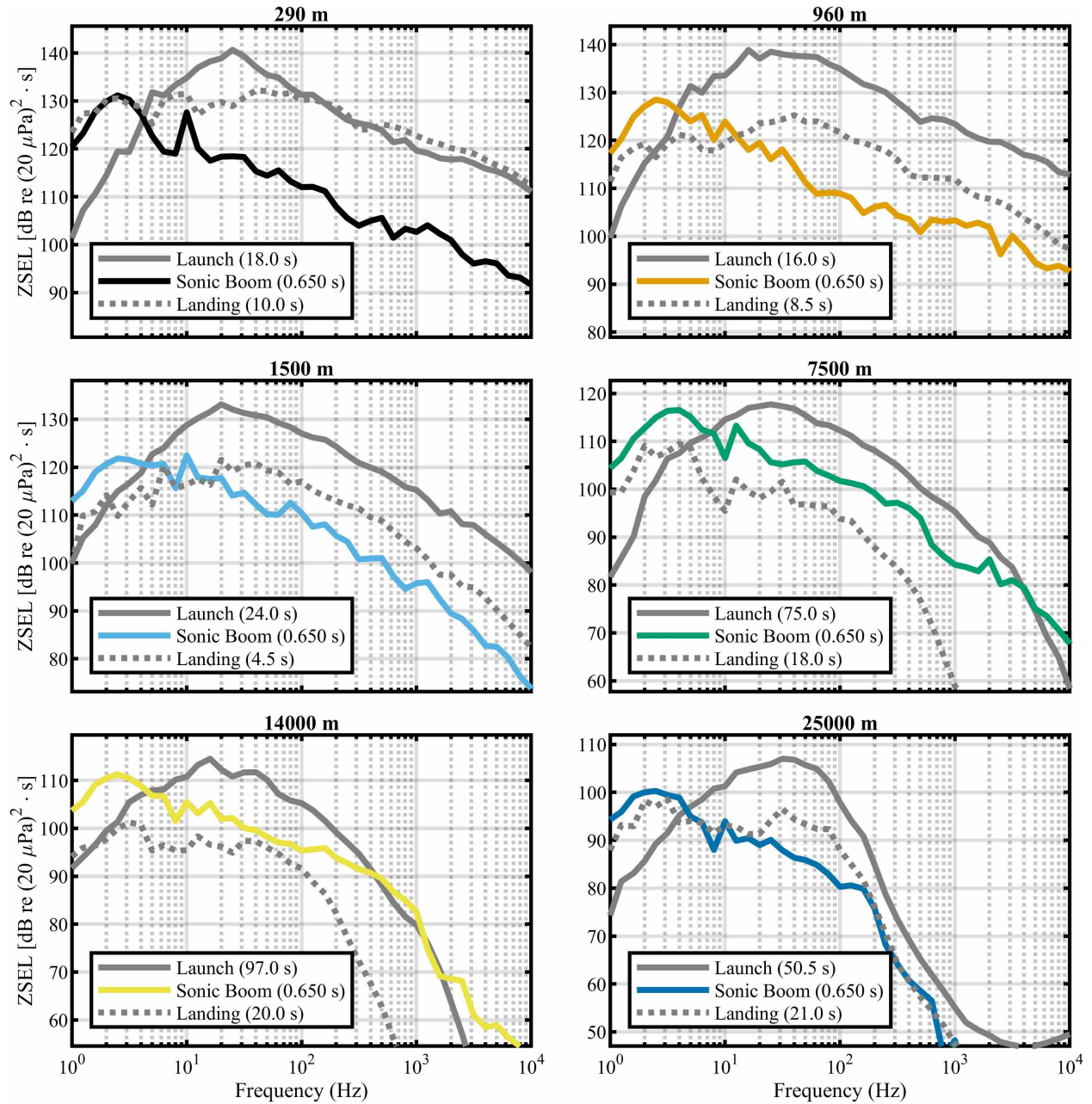


Figure 6.9 Comparing spectra across the different launch phases. Indicated above each sub-plot is the distance from the landing pad at which the measurements were made. The legend contains the duration of each recording used to produce the spectra. For the launch and landing noise, this was integrated over the 12 dB-down period of the signal while the sonic boom used a constant 650-ms recording. The colors used in this figure correspond to those used in Figs. 6.3 and 6.6.

When considering the peak overpressure, the sonic boom is even more important. At distances greater than 1–2 km from the landing pad, the sonic boom becomes the dominant peak-pressure event of the entire flight. When compared to just the landing noise, the sonic boom overpressure dominates the landing noise peak pressure at nearly all measured distances. At the measurement stations greater than 7 km, the sonic boom overpressure is a full order of magnitude greater than the landing noise peak pressure.

Comparing the spectra between the launch, sonic boom, and landing indicates that the sonic boom has a peak frequency that is lower than the launch by an order of magnitude. Meanwhile, the landing noise peak frequency shows no decipherable trend in the recordings used in this chapter. An additional interesting feature is that the high-frequency spectral rolloffs in several instances agree well between the three flight phases.

This chapter represents a preliminary analysis, and further analyses are needed to further study and characterize sonic booms from reusable rockets. There remain many unanswered questions regarding sonic booms generated by rockets upon landing. These questions are of both practical and scientific interest. For example, the ability to model the triple-boom waveform has not been shown yet (see Chapters 8–9), and current methodologies used rely on N-wave prediction methods. What modeling techniques are necessary to capture the triple boom? Why are the shocks in nearest and farthest measurement stations in the exact same positions within the waveforms? What is the effect of the third shock on sonic boom perception or structural response? What are the effects of these sonic booms on local communities and wildlife? Can any of these effects be reduced through sonic boom minimization techniques? These questions are important to help encourage the further reuse of space launch vehicles sustainably, and will only become more important as an increased number of rocket landings occur each year.

Acknowledgments

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Chapter 7

Analysis of Three Rocket Flyback Sonic Booms

Abstract

¹The SpaceX Falcon-9 rocket is a partially-reusable vehicle with a first-stage booster that lands propulsively after launch. As the booster falls toward the landing site, it produces a sonic boom. These sonic booms have unique properties and, so far, the ability to model them using current methods remains unclear. This paper presents findings from three Falcon-9 flyback sonic booms and highlights some features and trends that will be important to future modeling efforts. At every measurement location, a triple boom is recorded. This triple boom appears to propagate stably to at least 25 km from the landing pad. Within 1–2 km of the landing pad, the calculated sonic boom metrics tend to plateau. Outside 1–2 km of the launch and landing facility, the sonic boom is the highest-pressure event of the entire flight, including the launch. The Perceived Level 1 km from the landing pad is around 128 dB and at 25 km is around 87 dB. An appendix is included that discusses the benefits and challenges of attempting to correct for hardware low-frequency rolloff using digital pole-shift filtering.

¹This chapter is derived from a paper published in the Proceedings of Meetings on Acoustics with the following citation:

Anderson, M. C., Gee, K. L., Nyborg, K. (2024), “Flyback sonic booms from Falcon-9 rockets: Measured data and some considerations for future models.” *Proc. Mtgs. Acoust.* 54(1): 040005. <https://doi.org/10.1121/2.0001916>

© 2024 Acoustical Society of America. This material is reproduced here with permission. Minor changes have been made to fit within the context of this dissertation and to improve clarity and formatting. No conclusions or major results have been changed.

7.1 Introduction

To reduce costs and increase launch cadence, Space Exploration Technologies Corporation (SpaceX) flies the partially-reusable Falcon-9 rocket (SpaceX, 2026). The Falcon 9 has two stages: a booster that lifts the payload high into the atmosphere and a second stage that carries the payload to orbit. After the booster stage of flight is complete, the booster falls back through the atmosphere to land either on an ocean platform or back near the launch facility. Both the launch and landing phases of the flight are shown below in Fig. 7.1. In this chapter, the term “launch” is reserved for the ascent portion, the term “flyback” refers to the booster’s descent through the atmosphere toward the landing location either on land or at sea, and the term “landing” indicates the brief powered descent right before the booster touches down. The term “flight” encompasses the launch, flyback, and landing.



Figure 7.1 (Left) A SpaceX Falcon-9 rocket shortly after liftoff. (Right) A Falcon-9 first-stage booster landing. Credit for both photos: SpaceX (CC BY-NC 2.0 DEED License. No changes made).

During the Falcon-9 booster flyback, the booster descends from heights over 100 km at supersonic speeds, producing a sonic boom that can be observed for at least 25 km around the landing location (FAA, 2020b; Durrant *et al.*, 2023; Anderson and Gee, 2024). These sonic booms have three primary shocks (often referred to as a “triple boom”), rather than the two normally associated with far-field sonic booms (Maglieri *et al.*, 2014). Durrant *et al.* (2022a) found that 8 km from the launch and landing facility at Vandenberg Space Force Base (VSBF), the A-weighted sound exposure level (ASEL) for the sonic boom over 650 ms was 99 dB while the ASEL for the 27 highest-amplitude seconds of launch noise was 100 dB. Thus, while the sonic boom is brief compared to the launch noise, the overall sound exposure between the two can be comparable in the far field. Durrant *et al.* (2023) analyzed that same sonic boom measured at distances from around 0.3–14 km from the launch and landing facility. They found that at the farthest measurement stations, the ASEL for the sonic boom tended to be comparable to the ASEL over the 6 dB-down period of the launch noise. Additionally, they discovered that at distances greater than about 1 km from the launch and landing

facility, the sonic boom tended to become the highest-pressure event observed during the flight. Similar results were found by Anderson and Gee (2024), with the sonic boom being observed 25 km from the landing pad.

A Federal Aviation Administration (FAA) report from 2020 briefly discusses the sonic boom modeling approaches used by SpaceX (FAA, 2020b). When using NASA's PCBoom software in 2015 (Lonzaga *et al.*, 2022; Page *et al.*, 2023), SpaceX found that PCBoom tended to underestimate the near-field peak overpressures unless they used precise atmospheric information. SpaceX had more success using an adapted form of NASA's 1122 simplified sonic boom prediction method (Carlson, 1978). This adapted method, named "SpaceX 1122" within the report, included "... expansion of the geometry and simplifying relations to estimate the wave propagation to the ground". The SpaceX 1122 method tended to overestimate peak overpressures near the landing site but was deemed better overall. Their conclusion, as stated in the report, is

"SpaceX has measured and analyzed land landing overpressure data since 2015 and continues to rigorously optimize their adapted 1122 [model] to provide the most accurate and appropriate prediction for sonic boom data of a spacecraft vertical landing. [PCBoom] has been used in several instances and unless calibrated to account for precise atmospheric factors, this model can underpredict peak overpressures for Falcon first stage boosters. SpaceX believes the adapted 1122 model represents the most applicable overpressure predictions based on the accuracy of the results discussed above and the previous approved use in environmental consultations. SpaceX believes the precision would remain the same for the future Falcon 9 first stage booster landings, with the highest peak overpressure remaining between 6-7 psf [1 psf = 47.88 Pascals]. Based on the precision of the data presented, similar re-entry trajectories with the same vehicle would result in similar sonic boom magnitudes." (FAA, 2020b)

Although the SpaceX 1122 model seems simpler than the PCBoom model and may work for Falcon-9 peak overpressures, it may not generalize to other vehicles. Because the model appears to be tailored to match measured Falcon-9 peak-overpressure data, other waveform parameters might not be as accurately predicted. For example, the NASA 1122 model uses "... the assumption that the pressure signal generated by the aircraft is of the far-field type, the classical N-wave." (Carlson, 1978). Because the Falcon-9-booster flyback booms are not N-waves, any model based on NASA 1122 might not produce an accurate waveform shape. Predicting the triple boom may be particularly challenging because, to the authors' knowledge, no prediction of a triple-boom waveform from a Falcon-9 booster currently exists in the public literature (see Chapters 8–9).

The purpose of this chapter is to begin moving towards a more physical understanding of sonic booms produced by Falcon-9 rockets during flyback, in the hope that the global sonic boom community can begin to understand the physics behind these unique sonic booms. As more organizations fly and land reusable rockets, an understanding of the sonic booms produced will enable more-accurate predictions for effects on the community, wildlife, and structures. Additionally, future reusable rockets may incorporate more-precise predictions for sonic booms into the design process. To move toward these goals, this chapter compiles three Falcon-9 sonic boom measurement

campaigns performed at VSFB. These data can serve as a limited benchmark database for modeling Falcon-9 flyback sonic booms. The measurements are discussed in Sec. 7.2. The boom duration and shock positions are discussed in Sec. 7.3. Various sonic-boom metrics, including peak overpressures, rise times, and the NASA human perception metrics (Loubeau and Page, 2018), are shown in Sec. 7.4. A brief comparison to the launch noise is shown in Sec. 7.5. Lastly, the Chapter Appendix includes a discussion on the benefits and challenges of using digital pole-shift filtering to correct for hardware low-frequency rolloff (Rasband *et al.*, 2023; Marston, 2008).

7.2 Measurements

Brigham Young University (BYU) and California State University at Bakersfield (CSUB) completed three measurement campaigns to analyze the noise from different Falcon-9 flights at Vandenberg Space Force Base, CA. These measurements were performed during the SARah-1, Transporter-8, and SDA Tranche-0B missions. The SARah-1 and Transporter-8 measurements have been documented in greater detail by Durrant *et al.* (2023) and Anderson and Gee (2024) respectively, and the present chapter builds on many of the similar analyses from those papers by including multiple measurement campaigns. The SDA Tranche-0B measurement used the same types of hardware and microphone configurations as the other measurements. Two representative field setups are shown in Fig. 7.2. The microphone is inverted and placed above a convex, circular, plastic ground plate. The microphone is protected from wind and rain by a domed windscreen. Other electronics are kept in a weather-robust case. These setups have been specifically designed for rocket launch and sonic boom measurements (James *et al.*, 2020a; Gee *et al.*, 2020) and have been used in many launch vehicle noise data collection efforts (Hart *et al.*, 2022; Cunningham *et al.*, 2023; Gee *et al.*, 2023; Mathews *et al.*, 2023). As shown in Fig. 7.3, measurement stations, some of which were repeated across different flights to enable direct comparisons, were located between 0.3 and 25 km from the launch and landing facility. Because the peak frequency for these sonic booms is around 2–3 Hz (Anderson and Gee, 2024), digital pole-shift filtering was applied to all the measured data to improve the low-frequency responses (Rasband *et al.*, 2023; Marston, 2008). The Chapter Appendix contains further details on this process.

7.3 The Triple Boom

A unique feature of Falcon-9 booster flyback sonic booms is their triple-boom shape. Figure 7.4 shows waveforms measured during the three flights at two consistent locations. Although the waveforms do not match perfectly between flights, they all have three main shocks. Perhaps these triple booms could also be referred to as “M-waves”, which would closely connect them to classical “N-waves” while still emphasizing their triple-boom shape.

The triple boom is measured at every location for the three flights. Although similar-looking waveforms can be produced when an aircraft is accelerating along a flight track (Page *et al.*, 2015), such booms are produced only at a few locations, ruling out the possibility that the Falcon-9



Figure 7.2 Example measurement station consisting of an inverted microphone placed over a hard plastic ground plate and covered by a dome windscreen, with all other electronics placed inside a weather-resistant case. Some locations also included small weather stations mounted on tripods.

booster’s triple boom is the byproduct of sonic boom focusing due to acceleration. Another possible explanation was given by a SpaceX spokesperson, saying,

“[The] first boom is from the aft end (engines) . . . [The] second boom is from the landing legs at the widest point going up the side of the rocket. [The] third boom is from the fins near the forward end.” (Johnson, 2016)

This explanation deserves closer inspection, as it invites questions that may highlight future research needs. For reference, a schematic of the Falcon-9 booster during flyback is given in Fig. 7.5. The convex curvature near the widest point along a supersonic body tends to produce a rarefaction wave as discussed in Chapter 11 of Landau and Lifshitz (1987) and Chapter 9 of Anderson (2017), rather than a shock wave. This would indicate that the widest point of the folded landing legs is an unlikely source for a strong shock. However, perhaps the intended meaning is that the shocks produced by various portions near the top and bottom of the folded landing legs do account for the center shock. There are computational fluid dynamics simulations and wind tunnel experiments that support this theory (Bykerk *et al.*, 2022; Marwege *et al.*, 2019). During propagation, these shocks may coalesce into a single shock and account for the middle shocks seen in Fig. 7.4. As for the grid fins, Durrant *et al.* (2022a) argue that a small shock located shortly before the third shock could be caused by the grid fins while the final shock actually originates at the top of the interstage. This small shock is observed at several locations in the three measurements presented in this chapter, but not all. While there can be many theories for the triple boom origin, no full simulations starting from vehicle geometry and including propagation have been published, making it difficult to understand at present exactly what causes the triple boom.

The shock locations in the waveforms tend to be consistent at most measurement stations, as demonstrated in Fig. 7.6. Subplot (a) shows the total boom duration, or the time from the first shock

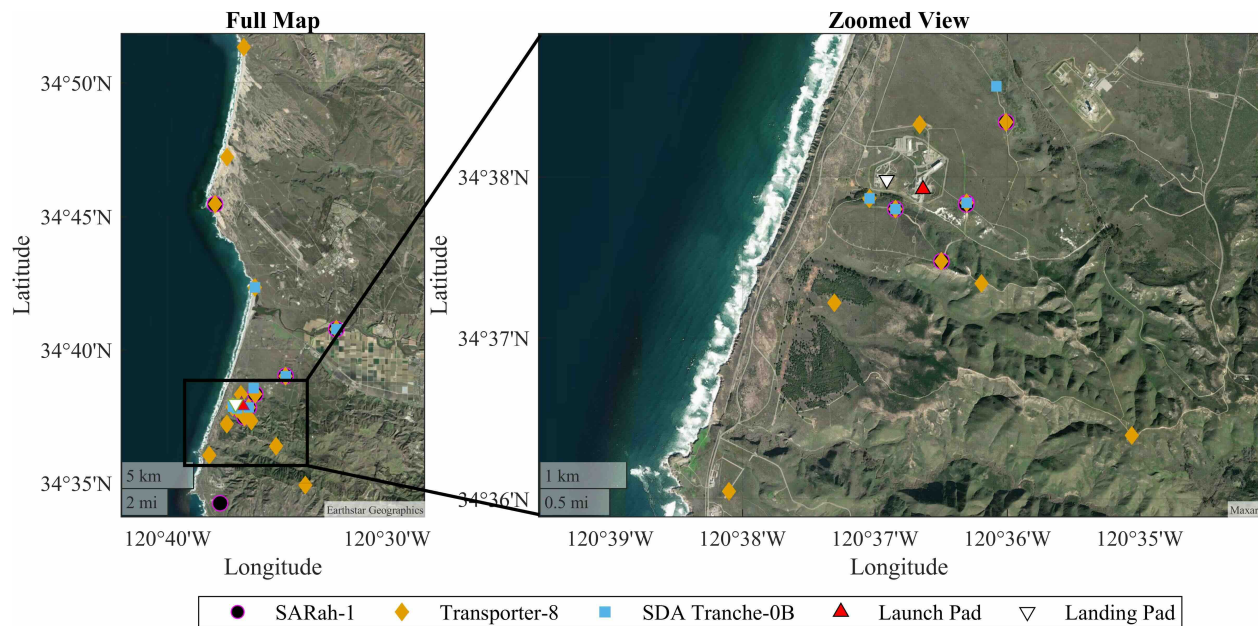


Figure 7.3 Measurement locations for the three flights. (Left) The full map. (Right) A zoomed-in map showing the stations nearest the pads. Imagery credit: Earthstar Geographics and Maxar.

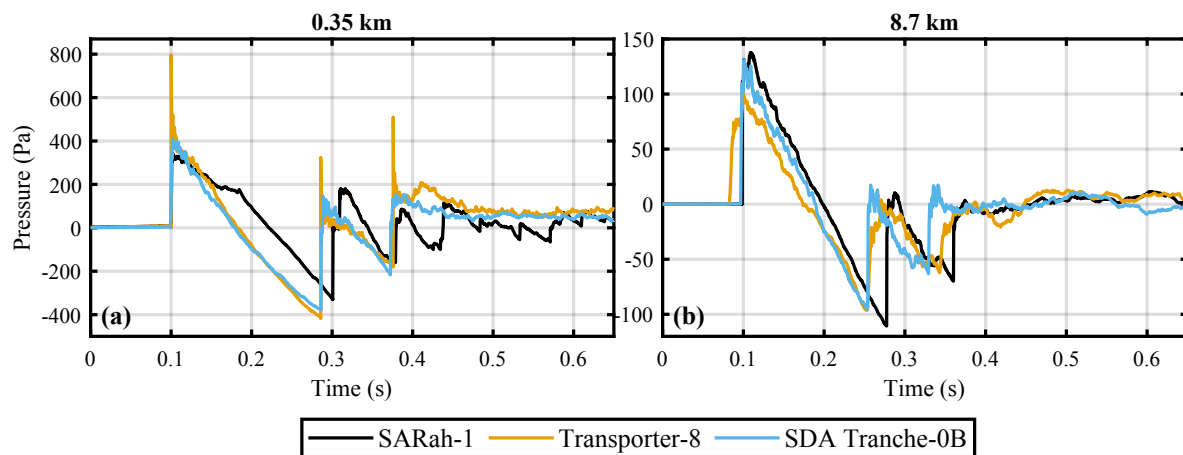


Figure 7.4 Example sonic boom waveforms from the three flights at distances of (a) 0.35 km and (b) 8.7 km from the landing pad. In (a) the SARah-1 third shock is partially conflated with noise produced by the booster engines, which are ignited shortly before the landing.

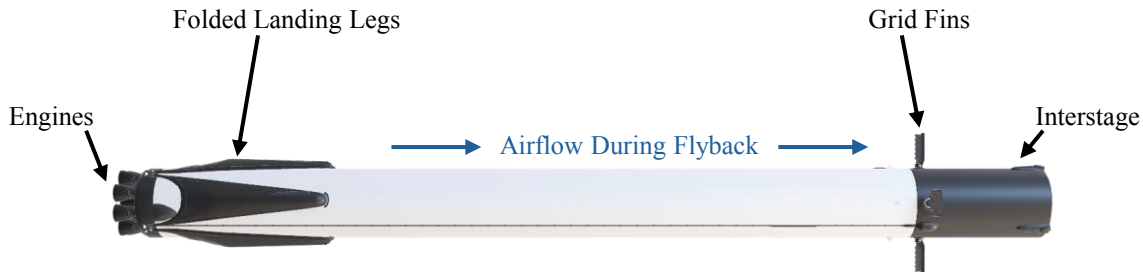


Figure 7.5 A schematic of the Falcon-9 booster during the flyback. The engines face the oncoming air. The landing legs remain folded until just before touchdown after the vehicle is subsonic. The grid fins are located near the bottom of the hollow interstage. 3D model adapted from Stanley Creative (2023) (CC BY 4.0 DEED License. Changes made).

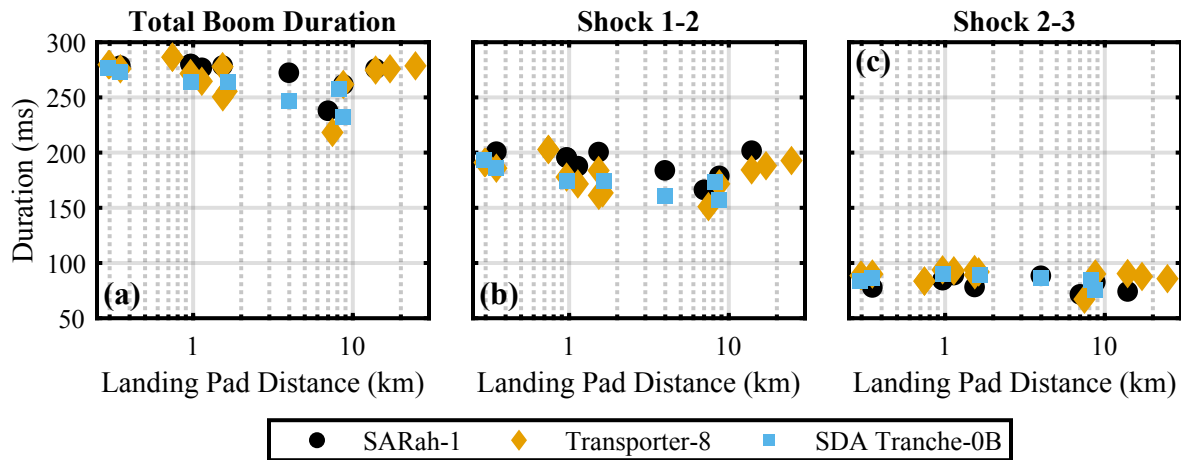


Figure 7.6 Duration between shocks. (a) The time between first and third shocks, or the total boom duration. (b) Time between first and second shocks. (c) Time between the second and third shocks.

to the third shock, while subplots (b) and (c) show the time between the first and second shocks, then the second and third shocks respectively. Most of the variability occurs between the first and second shocks, while the second and third shocks appear to generally have a constant time difference. The fact that booms measured 0.3 km and 25 km from the landing pad have nearly same duration is surprising because sonic booms tend to elongate with propagation distance (Maglieri *et al.*, 2014). While the sonic booms do not originate at the pad, but rather at some higher altitude, the sonic boom likely travels substantially farther to the farthest measurement stations than to the stations closer to the landing site. It is possible that waveform freezing may help account for the consistent shock locations (McLean, 1965; Hayes, 1967; Hayes *et al.*, 1968; Cleveland and Blackstock, 1996).

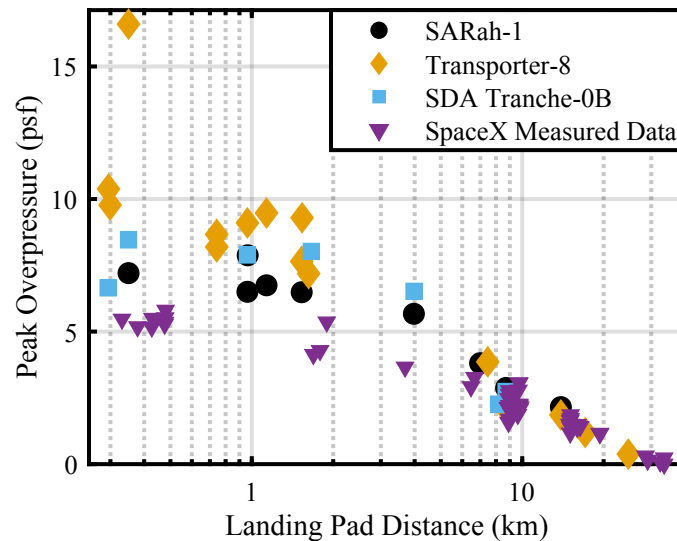


Figure 7.7 The sonic-boom peak overpressure in pounds per square foot as a function of distance from the landing pad. The SpaceX data are digitized from FAA (2020b).

7.4 Metrics

7.4.1 Peak Pressure and Rise Time

Analyzing the peak overpressure data from these three flights enables a direct comparison with measured SpaceX data (FAA, 2020b). This comparison is shown in Fig. 7.7. Farther than about 8 km from the landing pad, the sonic boom peak overpressures from these flights agree with the SpaceX measured data. Closer to the landing pad, all sonic boom peak overpressures from these three launches are consistently higher than the SpaceX data. The reason for this difference is unknown, but could be due to different return trajectories at VSFB compared to the Florida launch and landing sites, where the SpaceX data were obtained. It is also possible that the Falcon-9 booster design or typical landing trajectory has evolved enough to account for the difference since the time when these data were taken by SpaceX. Also noteworthy is the outlier at about 16 pounds per square foot (psf), the waveform for which is shown in Fig. 7.4(a) above. This particular waveform seems to have undergone turbulence-induced focusing, something common for other sonic booms (Maglieri and Sothcott, 1990; Maglieri *et al.*, 2014; Stout *et al.*, 2021). Other waveforms from these measurements show similar, less dramatic, signs of distortion. A study of how atmospheric turbulence affects Falcon-9 sonic booms has only recently begun (Nyborg *et al.*, 2024).

The rise times for these sonic booms are difficult to define. Typically, a sonic boom rise time is calculated by using the time between 10% – 90% of the peak overpressure (Maglieri *et al.*, 2011). As illustrated in Fig. 7.8(a), this definition has problems when the shock does not reach 90% of the waveform peak overpressure. This is a common occurrence for the Falcon-9 sonic booms measured during these three flights, where the true peak overpressure arrives after a delay that can be around

one to two orders of magnitude longer than the rise time of the shock. To work around this problem, Fig. 7.8(b) shows the front shock rise time from 10% – 50% of the waveform peak overpressure, denoted as the “half-rise time”. It is unlikely that this is the optimal approach to calculating the rise time, but it is sufficient for the present analysis to begin observing trends.

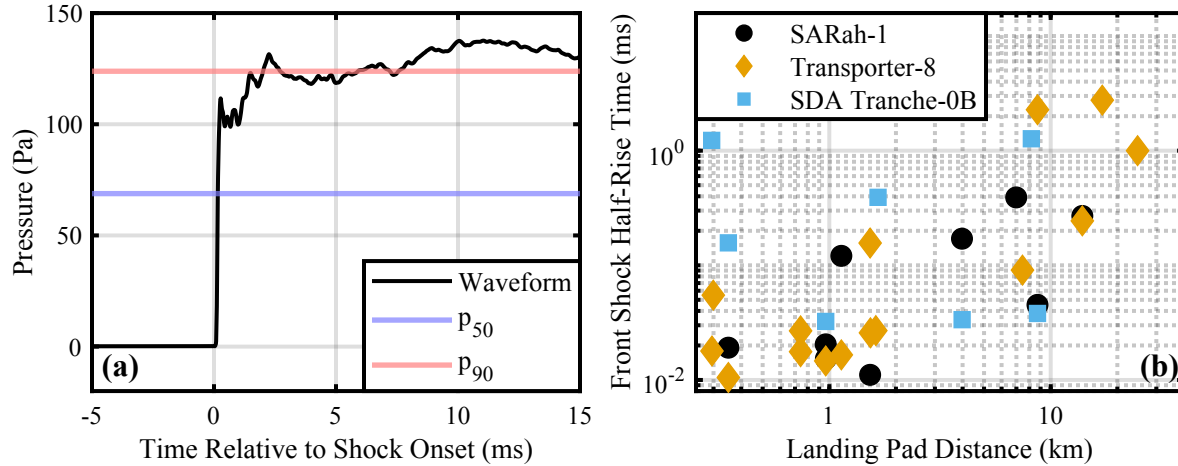


Figure 7.8 (a) An example waveform from SARah-1 at 8.7 km from the landing pad, illustrating that the p_{90} , or the point where the waveform reaches 90% of its peak overpressure, occurs after the first shock. The point where 50% of the peak pressure (p_{50}) is obtained is used in part (b) where sonic-boom front shock half-rise time for the three flights are shown as a function of distance from the landing pad.

For both the peak overpressures and front shock rise times, the data tend to plateau within about 1–2 km from the landing pad. This is also true for the metrics shown later in this chapter. A similar trend was noted by Durrant *et al.* (2023), but because only the SARah-1 data were considered for that paper, the sparsity of data resulted in the potentially-flawed conclusion that the sonic boom had a slower, cylindrical geometric decay rate. While sonic booms are generally considered to be cylindrical waves (Maglieri *et al.*, 2014), the explanation by Durrant *et al.* (2023) used the launch pad as the distance reference point. Because the sonic booms do not originate on the ground, but at some higher altitude, the exact distance from the source is difficult to determine, complicating an accurate estimation of the decay rate with distance. Thus the slower decay rate observed by Durrant *et al.* (2023) is probably the byproduct of trying to fit the plateauing data, something difficult to foresee without additional measurements. Perhaps the raytracing in PCBoom can be used in the future to better estimate the distance from the source to the receiver. Then a more-complete analysis of decay rate with distance can be performed.

Although not as rigorous as ray-tracing software, the plateau in the data can be qualitatively explained by considering the vehicle trajectory (Anderson and Gee, 2024). When viewing the live telemetry data (SpaceX, 2023), the booster tends to become subsonic while still a few kilometers above the landing site. Therefore, the rays intersecting the ground near the landing pad must be generated at these altitudes. Because all the locations near the pad are roughly equidistant from the

source, the sonic booms that reach those locations will all have propagated a similar distance, which could produce sonic booms with similar properties. For the farther measurement stations, the rays are generated higher and have more horizontal range to cover before reaching these locations, which could account for an overall decay in metric values with increased distance from the landing pad. This explanation qualitatively accounts for the plateau in metric values near the landing pad and the decay in metric values at farther distances.

7.4.2 NASA Sonic Boom Human Perception Metrics

NASA has determined several sonic boom metrics that tend to correlate with human annoyance (Loubeau and Page, 2018). These are the A-, B-, D-, and E-weighted sound exposure levels (SEL), a modified version of the Steven's Mark VII perceived level of loudness (PL) (Stevens, 1972; Shepherd and Sullivan, 1991), and the Indoor Sonic Boom Annoyance Predictor (ISBAP). The weighted SEL metrics, and including the C- and Z-weightings for completeness, are shown in Fig. 7.9. These metrics all tend to plateau at closer distances to the launch pad, as discussed above for the peak overpressure and rise time. Because these metrics are frequently calculated, providing them in this chapter enables comparisons to other sonic booms.

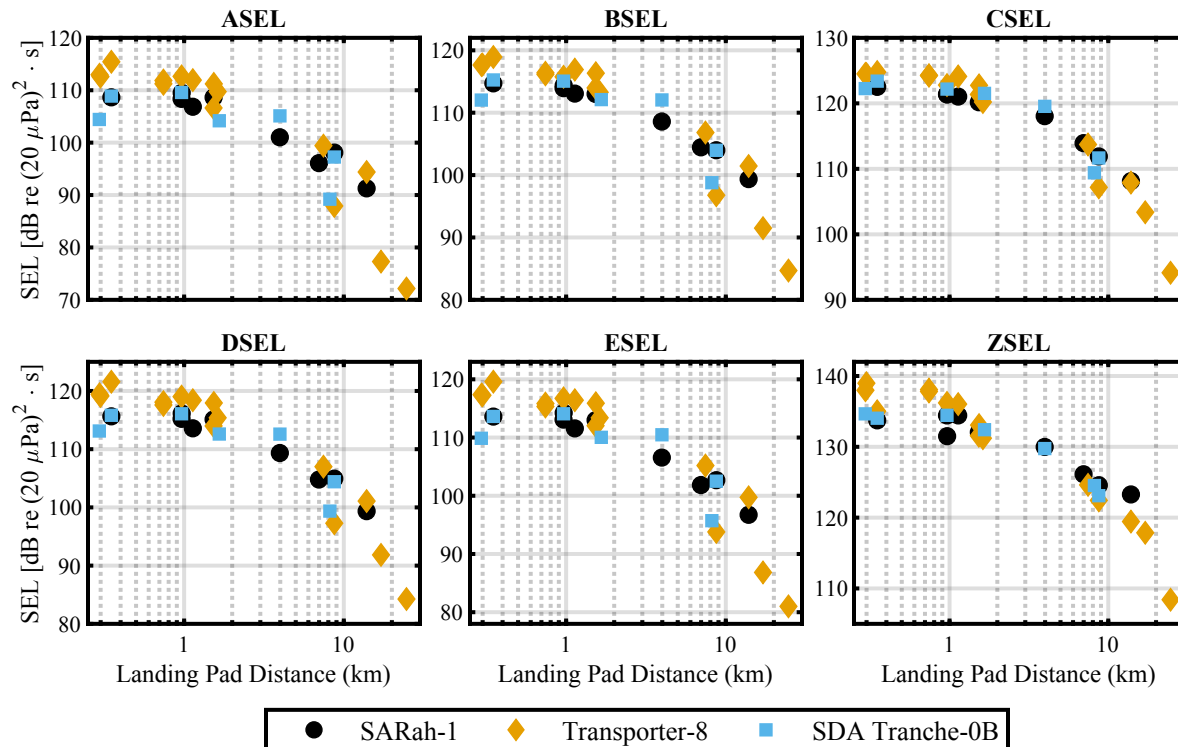


Figure 7.9 Six different sound exposure level weightings for the sonic booms from the three flights. The subplot titles denote which weighting is shown in each plot.

NASA's sonic boom metrics include two non-SEL measures, PL and ISBAP, which are both shown in Fig. 7.10. Included in Fig. 7.10(a) is the NASA target value for the X-59 quiet supersonic demonstrator (Doebler and Rathsam, 2020; NASA, 2026), indicating that the Falcon-9 sonic boom PL values are still about 10 dB higher than the target X-59 value at distances up to 25 km from the landing pad. Doeblner and Rathsam (2020) performed several experiments to help readers mentally calibrate the PL metric with other experiences. For example, a PL of 115 dB, about the same as being 5–10 km from the landing pad, is equivalent to a firework exploding 500 ft away. Personal experience by the authors indicates that this comparison would be accurate for fairly large fireworks. Doeblner and Rathsam (2020) also state that a PL of 125–130 dB, which occurs within about 2 km from the landing pad, is approximately equivalent to a gunshot measured from 2 ft away (without hearing protection). The authors have not come across X-59 targets for the other NASA sonic boom metrics.

Although these metrics are commonplace in aircraft sonic boom analyses because of their correlations with human perception, the authors know of no subjective studies of human or animal response to these unique Falcon-9 triple booms. Additionally, the NASA-modified PL metric carries with it the assumption of only two shocks (Shepherd and Sullivan, 1991), so its suitability for sonic booms with three shocks is unclear. This same problem arises for the ISBAP, which uses the PL as an input (Loubeau and Page, 2018).

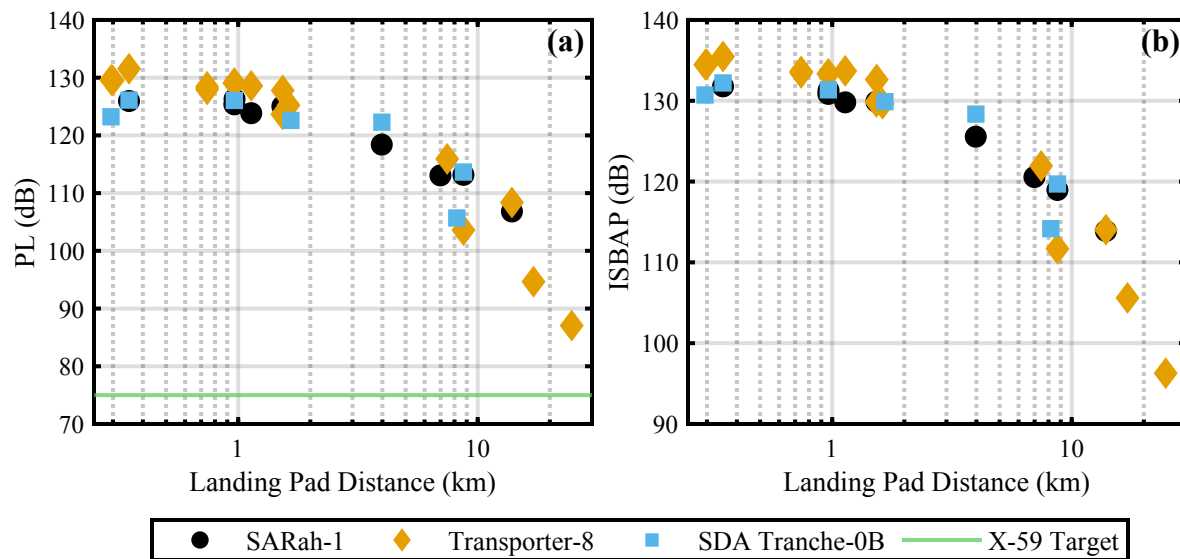


Figure 7.10 The (a) Perceived Level (PL) and (b) Indoor Sonic Boom Annoyance Predictor (ISBAP) for the sonic booms from the three flights. Also included in (a) is the target PL for NASA's X-59 quiet supersonic demonstrator aircraft (Doeblner and Rathsam, 2020; NASA, 2026).

7.5 Comparison to Launch Noise

The sonic boom represents a noise source comparable to the launch. Figure 7.11(a) shows the peak pressures for the launch and the sonic boom as a function of distance. Farther than 1–2 km, the sonic boom is the highest-pressure event of the entire flight, and that trend persists to at least 25 km. Figure 7.11(b) shows the ZSEL values calculated over the entire launch and the sonic boom. Farther than about 5 km, the sonic boom ZSEL can be comparable to the launch ZSEL. In other words, at those distances, the short 650-ms sonic boom recording can deliver as much sound exposure as the entire launch that precedes it. The ASEL is calculated the same way and is shown in Fig. 7.11(c). Farther than about 8 km, the sonic boom ASEL can be comparable to the launch ASEL, but not in every case. However, it is worth noting that the ASEL is unlikely to truly capture the human perception of either the launch or the sonic boom, considering that it essentially neglects the low peak frequencies for both (Gee *et al.*, 2023).

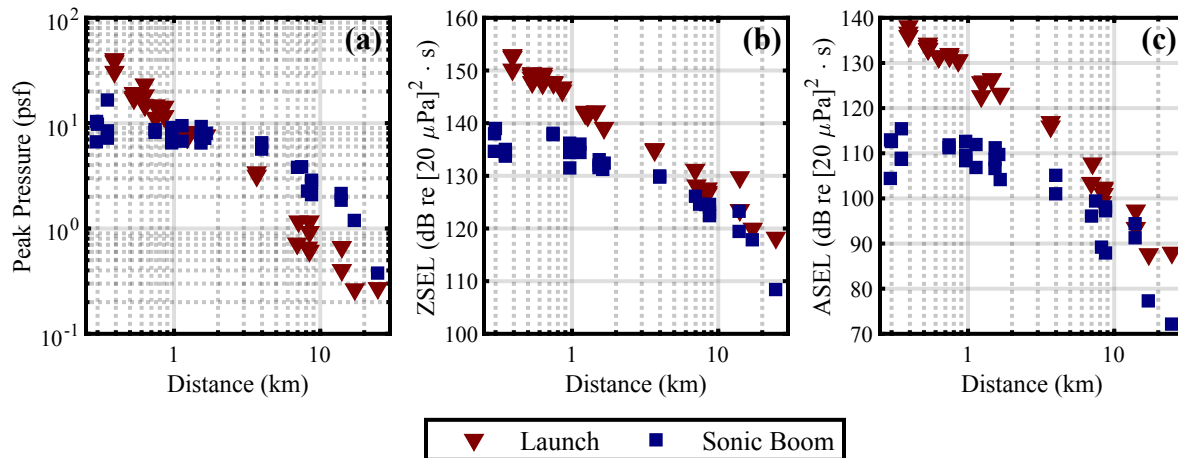


Figure 7.11 Comparing the (a) peak pressure, (b) ZSEL, and (c) ASEL between the launches and sonic booms. All three datasets have been combined for simplicity in these plots. The launch distance is relative to the launch pad and the sonic boom distance is relative to the landing pad.

7.6 Conclusion

The sonic booms produced by Falcon-9 boosters during flyback are unique compared to traditional aircraft sonic booms. At every measurement location for three different flights a triple-boom shape is observed. This unique triple boom appears to propagate stably with minimal shock movement or coalescence within the waveform out to at least 25 km from the landing site. All sonic boom metrics tend to plateau within 1–2 km of the landing site, and only decrease with distance for observers outside this radius.

When considering the peak pressure amplitudes and total sound exposure during a flight, the flyback sonic boom should be considered a major contribution. Farther than 1–2 km from the launch and landing facility, which are nearly collocated at VSFB, the sonic boom peak overpressure exceeds the peak pressures observed during the launch. Farther than 5 km from the facility, the ZSEL for the sonic boom alone can be comparable to the ZSEL over the entire launch preceding the sonic boom. Additionally, the sonic boom perceived level can exceed NASA’s current criterion estimate for human annoyance at distances as far as 25 km from the landing site.

Much work remains to be done in the area of launch vehicle flyback sonic booms. Both NASA’s PCBoom software and SpaceX’s modified NASA 1122 method have struggled to accurately predict the peak overpressures near the landing site (FAA, 2020b). Perhaps this is related to the metric plateau observed near the landing pad. Additionally, the ability to model a triple sonic boom from a booster flyback has not yet been clearly demonstrated within the scientific literature (see Chapters 8–9). So far, Falcon-9 sonic boom predictions and validations appear to have focused primarily on peak overpressures. While this is a good start, sonic boom perception is influenced by more than the peak overpressure alone, depending strongly on the shock rise times that determine the high-frequency energy content (Loubeau and Page, 2018).

A thorough understanding of the sonic booms produced during flyback will be essential as other organizations design and fly reusable launch vehicles. The ability to predict not just the peak overpressure, but also the full waveform and spectrum, will enable more-accurate environmental assessments. It may also become possible to intentionally alter the sonic boom shapes during the vehicle design process to better accommodate the local environmental and community noise criteria. As reusable rockets fly more frequently, research into the flyback sonic booms will enable a more-reliable approach to understanding the effects on structures, wildlife, and communities.

Acknowledgments

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7.7 Chapter Appendix: Extending Measurement Bandwidth to Lower Frequencies

Because the sound levels are highest near the launch and landing facility, quarter-inch microphones were used at closer locations. However, these microphones roll off at higher frequencies than the

half-inch microphones used at farther stations. Failing to accurately measure the low frequencies results in a distorted waveform. By assuming a low-frequency rolloff shape, the waveform and spectrum can be approximately restored using digital pole-shift filtering (Rasband *et al.*, 2023; Marston, 2008). A distorted waveform example from the Transporter-8 measurement is shown in Fig. 7.12, where two different microphones were deployed at the same location. One of the channels used a GRAS 47AC with a manufacturer-specified low-frequency cutoff of 0.09 Hz (GRAS, 2024b) and the other channel used a GRAS 46BE with a manufacturer-specified low-frequency cutoff of about 4 Hz (GRAS, 2024a). The GRAS 47AC channel, indicated in black in Fig. 7.12, most accurately resolves the true waveform shape. The GRAS 46BE channel, indicated in pink, has curved ramps between the shocks and tends to overshoot the peak pressures on the second and third shocks. After applying digital pole-shift filtering, the GRAS 46BE channel better approximates the GRAS 47AC measurement. This result is shown in green. Throughout this chapter, digital pole-shift filtering has been applied to all the data to approximately account for the low-frequency rolloff of both the microphones and data acquisition systems. In the future, the microphone responses can be precisely measured and a more-accurate correction can be applied.

Digital pole-shift filtering with quarter-inch microphones is challenging. Experience working with these microphones has indicated that the optimal cutoff frequency to use in the filter can deviate somewhat from the manufacturer specifications. This was noted by Rasband *et al.* (2023) to a lesser degree for half-inch microphones. For example, the published cutoff frequency for the GRAS 46BE microphone is 4 Hz (GRAS, 2024a), but in Fig. 7.12, an assumed input cutoff of 2.6 Hz was used to produce the green curves because it produced a closer match to the GRAS 47AC channel. To study this further, Fig. 7.13 shows sonic boom measurements using a seven-microphone probe deployed near the launch and landing facility during the SDA Tranche-0B measurement. These channels used GRAS 46BD microphones on NI 9250 cards. Figure 7.13(a) shows the raw measured data, with no attempt to correct the low-frequency response. Figure 7.13(b) shows the waveforms after digital pole-shift filtering with the default parameters as inputs (0.43 Hz for the NI 9250 card and 4.0 Hz for the GRAS 46BD). The low-frequency responses of the card and microphone were brought down using digital pole-shift filtering to 0.13 Hz and 0.10 Hz respectively. The waveforms are still somewhat distorted and don't agree with each other. Figure 7.13(c) shows the results after the input cutoff frequencies for the microphones have been tuned to produce a roughly-linear expansion between the first two shocks. These tuned parameters produce closer agreement between channels. The tuned cutoff frequencies, along with the peak overpressures, ZSEL, and ASEL for each channel in each subplot are shown in Table 7.1. The peak overpressure and ZSEL show the greatest sensitivity to the inputs, while the ASEL is hardly affected. This is because digital pole-shift filtering only affects the lowest frequencies, so metrics that tend to omit the low frequencies are not strongly impacted. The mean and standard deviations are also given in Table 7.1, providing an estimate of the uncertainty in each case. To simplify the analyses, the manufacturer specifications for cutoff frequency have been used throughout this chapter rather than custom-tailoring each channel. The uncertainties are not large enough to negate the trends observed in this chapter.

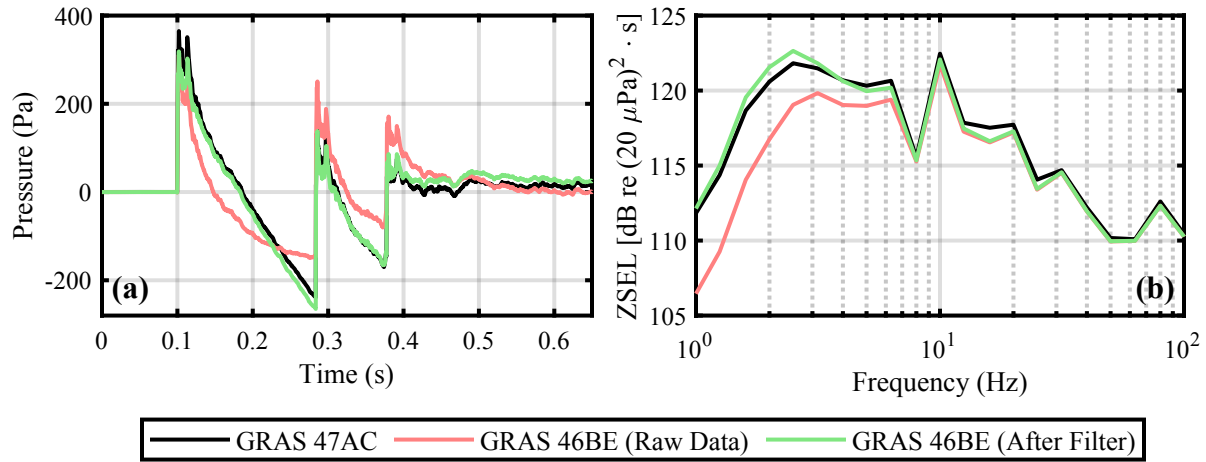


Figure 7.12 An example of restoring the low-frequency content in a sonic boom measurement. The colors represent channels using a GRAS 47AC (black), GRAS 46BE (pink), and the same GRAS 46AE after applying digital pole-shift filtering (green). Both channels used an NI 9250 card. (a) The waveforms. (b) The spectra.

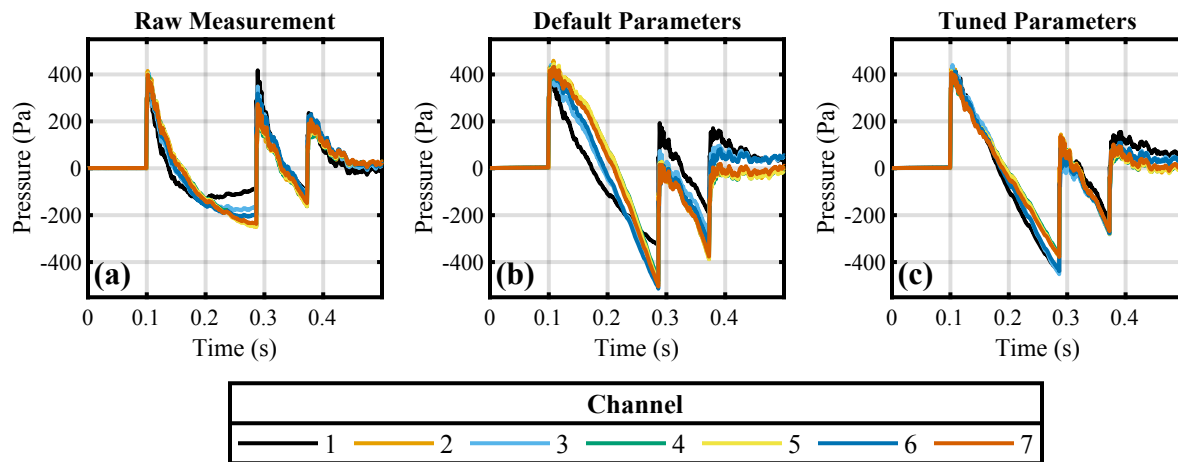


Figure 7.13 The effects of digital pole-shift filtering with different input parameters. (a) No filter applied. (b) The manufacturer-specified cutoff frequencies are used. (c) The cutoff frequencies have been tuned so the ramps between the first and second shocks are approximately linear.

Table 7.1 Metrics corresponding to all the waveforms in Fig. 7.13. Although those are plots trimmed in time, the metrics were calculated over the full 650-ms windows. The mean and standard deviation for each column is shown.

Channel	Tuned Cutoff (Hz)	Peak Overpressure (Pa)			ZSEL (dB)			ASEL (dB)		
		Raw	Default	Tuned	Raw	Default	Tuned	Raw	Default	Tuned
1	6.0	417.5	405.1	415.9	131.7	134.0	135.8	108.9	108.9	108.9
2	2.0	414.9	458.4	423.4	133.2	136.6	134.3	108.6	108.6	108.6
3	4.0	404.7	440.1	440.1	132.6	135.6	135.6	108.9	108.9	108.9
4	2.0	392.5	431.8	412.1	132.9	136.4	134.1	108.4	108.5	108.4
5	2.0	404.4	444.6	413.8	133.2	136.6	134.3	108.9	108.9	108.9
6	3.0	387.4	432.1	412.5	133.2	136.5	135.4	108.7	108.8	108.7
7	2.0	399.5	431.8	408.7	133.1	136.5	134.3	108.6	108.6	108.6
Mean	3.0	403.0	434.8	418.1	132.8	136.0	134.8	108.7	108.7	108.7
Stdev	1.5	11.0	16.3	10.7	0.6	1.0	0.7	0.2	0.2	0.2

Chapter 8

Initial Modeling of the Falcon-9 Triple Sonic Boom

Abstract

¹When the SpaceX Falcon-9 rocket booster descends through the atmosphere after a launch, it produces a sonic boom with three shocks in the far field, rather than the usual two-shock N-wave. In this chapter, the additional shock's origin is explained using sonic boom theory, nonlinear propagation modeling, computational fluid dynamics, and photographic evidence. The extra central shock results from a forward-migrating compression wave caused by the grid fins merging with a rearward-migrating rarefaction wave caused by the lower portions of the booster, including the folded landing legs.

¹This chapter is derived from a peer-reviewed letter published in the Journal of the Acoustical Society of America Express Letters with the following citation:

Anderson, M. C. and Gee, K. L. "Why does the Falcon-9 booster make a triple sonic boom during flyback? An initial analysis," JASA Express Lett., Vol. 5, No. 2, 2025, p. 023601. <https://doi.org/10.1121/10.0035649>.

© 2025 Authors. This work is licensed under a Creative Commons Attribution (CC BY 4.0) license. Minor changes have been made to fit within the context of this dissertation and to improve clarity and formatting. Additionally, the computational fluid dynamics description has been updated to correct an error in simulation Mach number. No conclusions or major results have been changed.

8.1 Introduction

The SpaceX Falcon-9 rocket is the first orbital-class launch vehicle with a fully-reusable booster stage (SpaceX, 2026). The 41.2-m long booster separates from the rest of the rocket while in the upper atmosphere and then descends through the atmosphere toward a landing pad either on land or at sea. Examples of a launch and landing are shown in Fig. 8.1(a) and (b) respectively. Because the booster descends at supersonic speeds, it produces a sonic boom (Anderson *et al.*, 2024c), referred to as a “flyback sonic boom”. While most far-field sonic booms are N-waves (i.e., consist of two shocks) (Maglieri *et al.*, 2014), these booster-flyback sonic booms contain three primary shocks (Anderson *et al.*, 2024c; Anderson and Gee, 2024), as shown in Fig. 8.1(c) and (d). This phenomenon is not unique to the Falcon-9 booster, as the SpaceX Starship Super Heavy booster’s sonic boom also has shown three distinguishable shocks (Gee *et al.*, 2024b). Understanding the Falcon-9 triple sonic boom may therefore shed light on whether all reusable rocket boosters are expected to produce a similar signature.

Such flyback sonic booms are high-amplitude acoustic events. Measured data from three Falcon-9 flights have been published by Anderson *et al.* (2024c). For observers farther than 2 km from the launch and landing locations, the sonic boom peak overpressure exceeds the peak pressures experienced during the launch. Within 2 km of the landing location, the sonic boom peak overpressures are generally between 6–10 pounds per square foot (psf, with 1 psf = 47.88 Pascals). This drops to 2–3 psf at 10 km, with the triple sonic boom being clearly measured as far as 25 km from the landing pad, and likely persisting even farther.

In the modern space age, other organizations throughout the world are also developing reusable vehicles that will use a similar flyback approach. Because this will result in an increase in the number of sonic booms around the landing facilities, it is important to ensure that accurate launch vehicle sonic boom models are developed and used. Sonic boom prediction software, like NASA’s PCBoom software (Lonzaga *et al.*, 2022; Page *et al.*, 2023), has generally been designed and validated for use with air-breathing, aerodynamic-lift-producing jet aircraft, rather than rockets and reentry vehicles. Thus, these vertically-descending, rapidly-decelerating, blunt-body sonic boom sources provide a unique opportunity to further understand sonic boom formation and propagation. Although some organizations have used current models to produce prediction maps for Falcon-9 flyback sonic booms (FAA, 2020b), such results only show final metric values, rather than full waveforms. This leaves whether the physics are fully understood and modeled as an open question. Some evidence suggests that models have been custom-tailored to match specific launch vehicles (FAA, 2020b). This can be useful for predicting the sonic booms from a known vehicle under certain atmospheric and trajectory conditions, but does not necessarily produce a model that can be confidently ported to a new vehicle design or to other flight conditions.

Although there are many interesting features of Falcon-9 flyback sonic booms, this chapter’s aim is restricted to determining why the booster produces a triple sonic boom rather than an N-wave. Although the effects of maneuvers are important for sonic boom predictions (Lonzaga *et al.*, 2022; Maglieri *et al.*, 2014), a maneuver-based explanation would not explain why a consistent triple sonic boom is measured at all locations ranging from near the landing pad to 25 km from the pad, and at all azimuths (Anderson *et al.*, 2024c). Additionally, the triple boom cannot be due to the

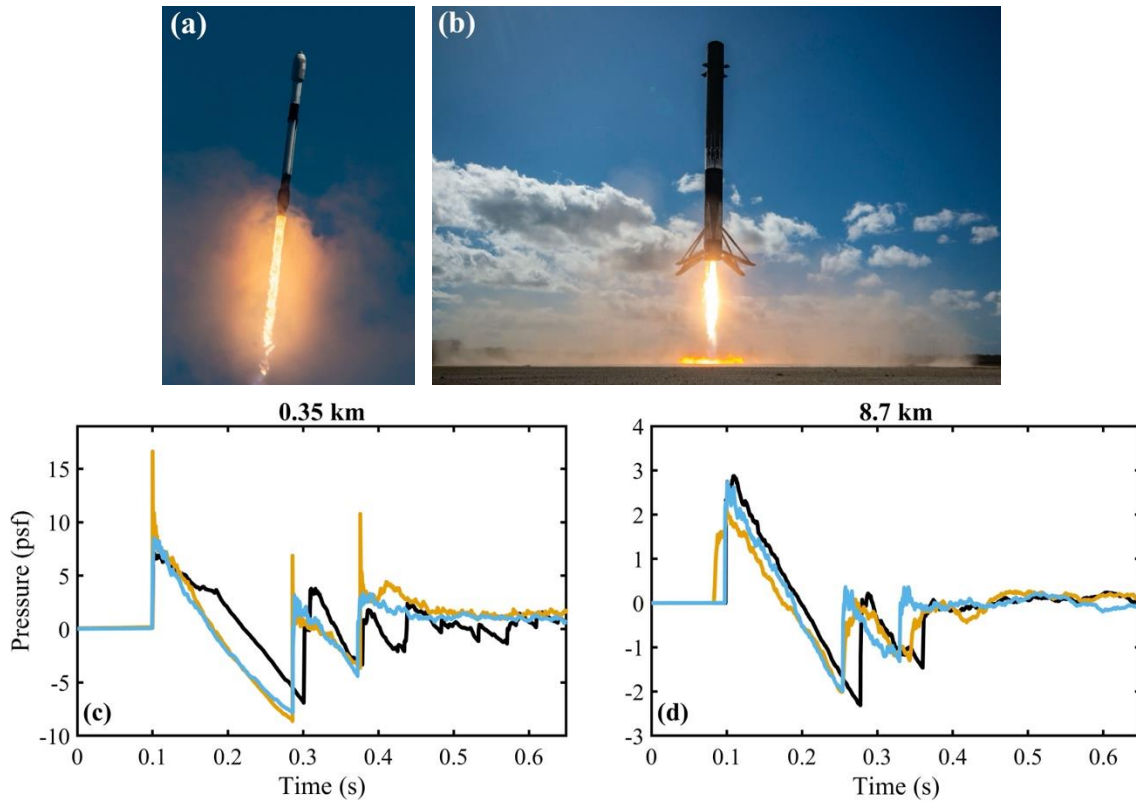


Figure 8.1 (a) A full Falcon-9 launch vehicle on ascent. (b) The booster stage shortly before landing. (c) Triple-boom signatures measured 0.35 km from the landing pad during three separate flights, measured in pounds per square foot (psf). The measurement colored in black is conflated with other landing-related noise. (d) Triple-boom signatures measured 8.7 km from the landing pad during the same three separate flights, also in psf. Both (c) and (d) were reproduced from data in Anderson *et al.* (2024c), with minor processing and plotting differences here. [Credit for photographs (a) and (b): SpaceX (CC BY-NC 2.0 DEED License. No changes were made).]

exhaust plume from the engines during the landing burn, as the landing burn tends to occur after the vehicle is subsonic (see SpaceX (2023) for an example). Thus, because the booster falls without engines on during the majority of the time that the sonic boom is produced, an explanation based on booster geometry is preferable. Such an explanation is demonstrated in this chapter using three complementary approaches. It should be noted that because this is an initial analysis, the primary goal is to see whether a triple sonic boom can be predicted in the far field, and the precise matching of that sonic boom to measurements remains an important part of future work. The first method, shown in Sec. 8.2, uses sonic boom theory coupled with nonlinear acoustic propagation modeling. In Sec. 8.3, computational fluid dynamics (CFD) simulations are used to visualize the flow field near the booster during flyback. In Sec. 8.4, photographic evidence from a booster flyback is used to

visualize portions of the flow during an actual flight. Each method supports the conclusion that the booster's grid fins produce a forward-migrating shock wave that merges with a backward-migrating rarefaction wave produced by the lower portions of the booster, including the folded landing legs. This merging produces an additional central shock, explaining the triple boom signature.

8.2 Method A: Sonic Boom Theory and Nonlinear Propagation

8.2.1 Determining a Suitable F-function

Classical sonic boom theory can be used to provide estimates for sonic boom properties in the far field. Because the Falcon-9 booster is not a simple geometric shape, many simplifying assumptions are made, as will be discussed throughout this section. The pressure field surrounding an axisymmetric body of revolution can be approximately described (Whitham, 1952; Gottlieb and Ritzel, 1988; Maglieri *et al.*, 2014) as

$$\delta p = \frac{p_a \gamma M_\infty^2}{(2\beta r_0)^{1/2}} F(\chi), \quad (8.1)$$

where δp is the pressure change from ambient, p_a is the ambient pressure, γ is the ratio of specific heats, M_∞ is the freestream Mach number, β is equal to $\sqrt{M_\infty^2 - 1}$, r_0 is the radial distance away from the projectile at which the pressure is to be determined, and $F(\chi)$ is known as the “F-function”, where $\chi = x - \beta r$ is the location along Mach lines, with x being the physical location along the booster. The F-function describes the vehicle geometry in a way that translates into an acoustic propagation field via Eq. (8.1). Following a recommendation from Carlson and Mack (1977) for blunt bodies, the F-functions in this chapter are calculated along the coordinate x instead of χ . This accounts for the fact that shock waves produced by blunt bodies do not initially travel along Mach lines. Whether this assumption holds for intermediate features along an elongated blunt body like the Falcon-9 booster is unclear, but for the current study it is assumed to be a reasonable approximation. Applying this coordinate change, the F-function is defined as

$$F(x) = \frac{1}{2\pi} \int_0^x \frac{A''(\bar{x})}{\sqrt{x - \bar{x}}} d\bar{x}, \quad (8.2)$$

where A'' is the second derivative of the cross-sectional area as a function of distance along the body. Note that the booster is assumed to be falling with zero angle of attack relative to the oncoming air. In reality, the booster does have a non-zero angle of attack, which would produce a lift component in the F-function definition. While the effect of this lift on the sonic boom is an important topic for future study, only the simple case of a zero-degree angle of attack is considered here.

In this chapter, the booster is modeled as an axisymmetric body of revolution with protuberances representing the landing legs and grid fins. While the vehicle is not completely axisymmetric, the triple boom is observed at all azimuth angles relative to the landing location (Anderson *et al.*, 2024c), which leads to the assumption that the flow field blends azimuthally during propagation. For simplicity, this blending is inherently accounted for by assuming an axisymmetric body from the start.

This modeling has two levels of detail. Figure 8.2(a) shows the booster modeled as a simple cylinder of equal proportions to the booster. Both the original geometry (black) and a modified geometry (blue) designed to better match an effective body shape are shown. Throughout this chapter, this geometry is referred to as the “Cylinder”. The F-function for this geometry is shown in Fig. 8.2(b). A more detailed approximation to the booster geometry is shown in Fig. 8.2(c), including the folded landing legs, grid fins, and a small protuberance near the top of the booster. Throughout this chapter, this geometry is referred to as the “Falcon 9”. The F-function for this geometry is shown in Fig. 8.2(d).

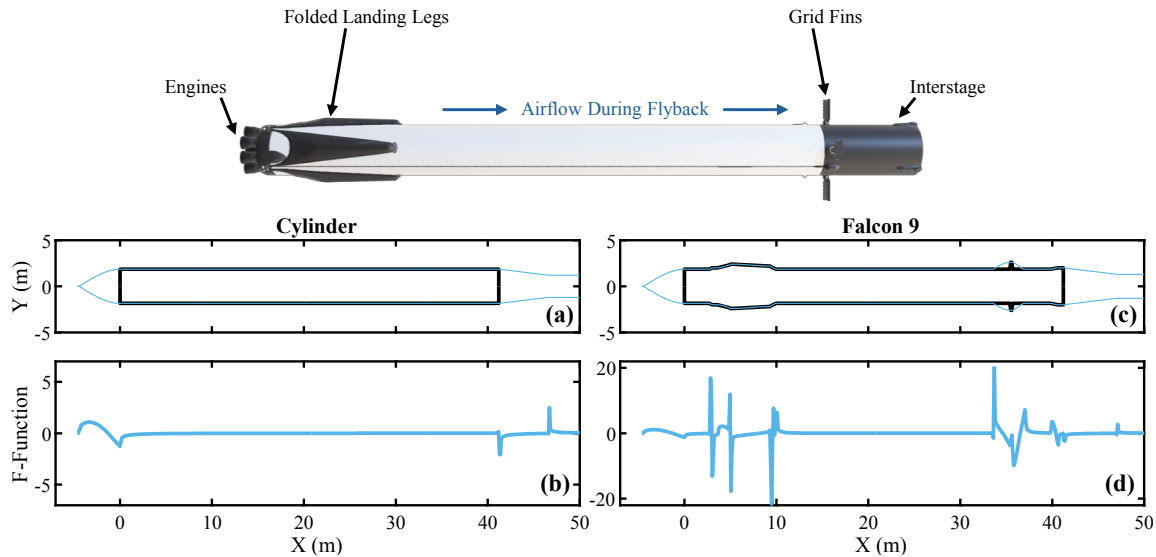


Figure 8.2 (Above) An annotated Falcon-9 booster model during flyback. (a) A cylindrical geometry of comparable dimensions to the booster. The original geometry is shown in black while the blue shows a slightly modified geometry according to principles discussed by Gottlieb and Ritzel (1988). (b) The F-function for the cylindrical geometry at Mach 2. (c) similar to (a), but for the Falcon-9 booster geometry. (d), similar to (b), but for the Falcon-9 booster geometry at Mach 2. [3D model adapted from Stanley Creative (2023) (CC BY 4.0 DEED License. Changes made).]

To account for the blunt shape of the booster during flyback (see Fig. 8.2), methods proposed by Gottlieb and Ritzel (1988) are applied to ensure more accurate shock placement. Because the goal is to model the far-field boom waveforms, it is assumed viable to accurately model only the general flow field, rather than to accurately match every detail of the geometry, as the near-field details will tend to disappear during propagation (Maglieri *et al.*, 2014). There are three blunt features to which corrections are applied: the bottom of the booster (where the engines are located), the grid fins located near the top of the booster, and the actual top of the booster where there is an abrupt end to the geometry. These are all visible in Fig. 8.2. Although some other portions of the booster may

also be considered blunt, the corrections that could be applied to these areas are assumed to have minimal impact on the far-field signature.

At the bottom of the booster, there is a detached bow shock. To account for the standoff distance between the shock and the body of the booster, an artificial body extension is added, ensuring that the shock occurs at the proper location. This is done for both the Cylinder and Falcon-9 geometries shown in Fig. 8.2. This extension can be represented by a cubic polynomial subject to the boundary conditions specified by Gottlieb and Ritzel (1988). Using the highly-blunt Falcon-9 geometry, the original recommendation provided by Gottlieb and Ritzel (1988) produces an updated geometry that still greatly exceeded their suggested bluntness criteria. To correct for this, a related equation intended for blunt features on other portions of the geometry was used and found to more closely align with their bluntness criteria. This resulted in a larger standoff distance between the bow shock and the bottom of the booster.

The grid fins on the booster represent the most challenging aspect of this geometry. The fins allow airflow through the grid-fin structure while still producing a shock ahead of the fins. This can be observed in wind-tunnel and CFD work by Bykerk *et al.* (2022). Although Gottlieb and Ritzel (1988) did not consider blunt features that allow flow through, we treat it as a smaller protrusion than the physical grid fins. As shown in Fig. 8.2(c), the grid fins are modeled as a solid protuberance that extends about half as far as the physical grid fins. The shorter size ensures that airflow is not altogether impeded while ensuring that a shock is still produced. To model the flow on the other side of the grid fins, a linear taper in the geometry is used that returns the geometry radius to the same as the booster. Future research should investigate the most appropriate treatment of grid fins in sonic boom modeling.

For blunt features that face away from the flow such as the top of the booster, a different type of extension is applied to the body. This extension accounts for the flow after the body and the subsequent turbulent wake. The first portion of the extended geometry is a conical shape behind the top of the booster. The cone tapers to an amount specified by Gottlieb and Ritzel (1988) and then becomes a cylinder. This is used for both the Cylinder and Falcon-9 geometries in Fig. 8.2.

8.2.2 Propagation

After the F-functions have been converted to pressure disturbances via Eq. (8.1) (using $r_0 = 41.2$ m, or one body length away from the vehicle), they are propagated using the generalized Burgers equation for cylindrical spreading (Hamilton and Blackstock, 2024):

$$\frac{\partial p}{\partial r} = \frac{\beta}{2\rho_0 c_0^3} \frac{\partial p^2}{\partial \tau} + \bar{\Psi}p - \frac{1}{2r}p \quad (8.3)$$

where p is the pressure disturbance, r is the propagation distance, β is the coefficient of nonlinearity taken to be 1.201 in air, ρ_0 is the ambient density, c_0 is the ambient sound speed, τ is the retarded time, and $\bar{\Psi}$ is an operator that acts on the pressure and represents the effects of atmospheric attenuation and dispersion.

This equation is solved numerically using a hybrid time-frequency approach. The methods are described more completely in Gee (2005) and Gee *et al.* (2008). Waveform distortion is calculated in

the time domain via the Earnshaw solution while the geometric spreading, atmospheric attenuation, and dispersion are calculated in the frequency domain. The method uses adaptive steps based on the shock-formation distance (Anderson, 1974). When the steps are less than 1 mm, the method of Pestorius (Pestorius, 1973; Hamilton and Blackstock, 2024) is used to determine shock location and amplitude.

As the signatures are input into the equation, they are converted to functions of time using an assumed mean sound speed of 343 m/s and are resampled to 20 kHz. The time arrays are then scaled by $1/M_\infty$ to account for the fact that far from the vehicle, the waves approximately follow the Mach lines and thus the shocks are closer to each other than if they all propagate normal to the geometry. Additionally, when the initial pressure field calculated using Eq. (8.1) is input into Eq. (8.3), the pressures are large. For the Cylinder geometry, pressures around one atmosphere are estimated at one body length away from the booster (41.2 m). For the Falcon 9 geometry, the peak pressure excursions are around 10 atmospheres at the same distance. Such pressures are clearly nonphysical, as the rarefactions would be below vacuum pressure. This could be fixed by calculating the pressure at a farther distance in Eq. (8.1), but the required distance to have the pressure excursions drop to within one atmosphere would be around 100 body lengths, by which distance the near-field source function produced via the F-function is no longer valid, as Eq. (8.1) does not account for the nonlinear effects that would have substantially altered the flow field. Fortunately, when the signature at one body length away from the booster is input into Eq. (8.3), the peak overpressures rapidly decay to less than one atmosphere within the first 2 meters of propagation. Within the first 7 meters, the peak overpressures decay to within 0.5 atmospheres. Thus, outside of the first few meters of propagation, the flow field is assumed to be sufficiently accurate to capture the overall far-field sonic boom shape when propagated, though the overpressures are not expected to be fully accurate. This claim is substantiated by the similarity between the signatures produced in this section with the flow fields shown using computational fluid dynamics in Sec. 8.3. For both the Cylinder and Falcon 9 cases in this chapter, the signatures calculated at one body length away from the booster are used. As the purpose of this chapter is to describe the overall waveform shape in the far field, this is an acceptable limitation. Future work should go toward accurately modeling both the waveform shape and overpressures simultaneously.

As the Cylinder and Falcon-9 near-field signatures are propagated to the far field, the two signatures evolve into, respectively, an N-wave and a triple boom. This propagation is animated in Mm. 1. In this animation, the Cylinder geometry produces a shock followed immediately by a rarefaction wave. This rarefaction wave ultimately migrates backward in the pressure signature and merges with the recompression shock near the top of the Cylinder. Although an interesting feature, we expect this rarefaction wave is not fully accurate. While the methods used here are essentially laminar, studies of turbulent supersonic flow over forward-facing steps indicate that turbulent separation can greatly complicate the flow field near the geometric discontinuity (Czarnecki and Jackson, 1975; Murugan and Govardhan, 2016; Hu *et al.*, 2022). Additionally, Gottlieb and Ritzel (1988) suggest that inaccurate expansion waves can be generated near the front of blunt geometries when using F-function methods. Krasnov (1970) also discusses the flow around a body of revolution with a flat nose and shows that turbulence is an important consideration, forming a region of separated flow followed by a reattachment shock. While the accuracy of this rarefaction wave

remains under investigation, the Cylinder signature does evolve into an N-wave. It is thus concluded that the far-field signature from a cylindrical geometry of equal proportions to the Falcon-9 booster is an N-wave, though a relatively large propagation distance may be necessary for the N-wave to fully develop from this geometry.

Mm. 1. Animation of both the Cylinder and Falcon-9 near-field signatures being propagated out to the far field. Pressure axes are changed based on the waveform amplitudes and are equal for both plots. The simulations were run at Mach 2.0. The animation can be found at <https://doi.org/10.1121/10.0035649>.

While the Cylinder geometry produces a far-field N-wave, the Falcon-9 geometry produces a triple boom that remains stable out to at least 25 km, as has been observed in measurements (Anderson *et al.*, 2024c; Anderson and Gee, 2024). Although the Falcon-9 geometry also produces a rarefaction wave at the base of the geometry, it is of little consequence as the rarefaction wave is almost immediately negated during propagation by a forward-migrating shock produced by the folded landing legs. This shock then merges with the front shock of the waveform. The folded landing legs also produce another, separate, rarefaction wave. As this rarefaction wave migrates backward in the signature, it merges with a forward-migrating shock wave produced by the grid fins. This produces a central shock that is more balanced and remains near the center of the signature. Thus, it is concluded that the far-field signature from a Falcon-9 booster geometry is a triple sonic boom.

To further illustrate and compare the changes in the waveforms with propagation distance, the signatures at four different distances are shown in Fig. 8.3. As the two signatures propagate, the Cylinder case produces an N-wave while the Falcon-9 case produces a triple sonic boom. These results demonstrate that a triple sonic boom can be predicted in the far field based on the booster geometry and that the triple sonic boom origin is likely related to the intermediate features of the geometry, particularly the grid fins. Because there remains some ambiguity over the accuracy of the rarefaction wave produced at the bottom of the geometry, the conclusion of this portion of the analysis is that the central shock results from a forward-migrating compression wave caused by the grid fins merging with a rearward-migrating rarefaction wave caused by the lower portions of the booster, including the folded landing legs. Further studies are required to determine the precise effects of the landing legs on the final far-field signature.

8.3 Method B: Computational Fluid Dynamics

The second method used to determine the triple-boom origin is computational fluid dynamics (CFD). The results are shown in Fig. 8.4. For these simulations, two-dimensional unstructured meshes for both the Cylinder and Falcon-9 geometries were produced in GMSH (Geuzaine and Remacle, 2024) and the simulations were run in OpenFOAM (OpenFOAM, 2024). The simulations were run at Mach 1.5 with the *shockFluid* solver for compressible flows. To reduce computational complexity, the flow field was assumed to be laminar. Assuming symmetry, the flow was only computed on

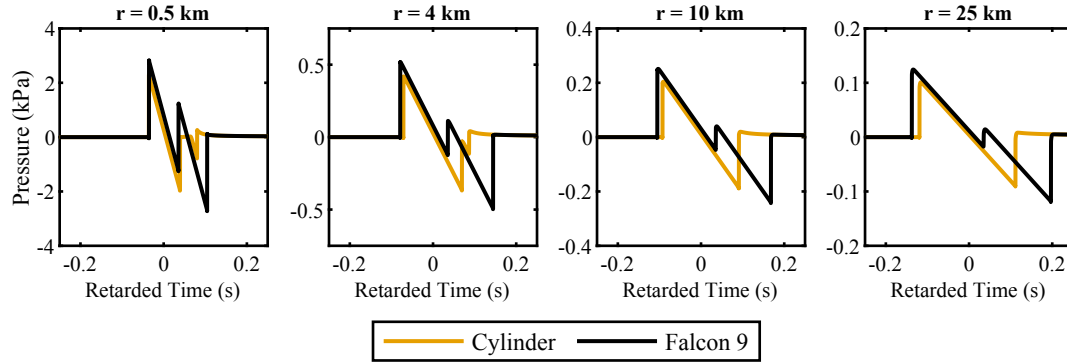


Figure 8.3 Propagation of the pressure signatures estimated at one body length from the booster to distances of 0.5, 4, 10, and 25 km. These cases were run at Mach 2.0.

one side of the geometries, with a *symmetryPlane* boundary condition on the bottom. The portions where the geometries were modeled used a *zeroGradient* boundary condition for the pressure and temperature and a *slip* condition for the velocity. Flow entered through the left boundary and exited through the top and right boundaries, which used *waveTransmissive* boundary conditions.

For the Cylinder geometry, three features persist at the edge of the computational domain. These arise from the detached bow shock, a rarefaction occurring at the base of the booster, and a recompression shock at the end of the geometry. Similar results were found in Sec. 8.2, where the central rarefaction wave in that analysis ultimately merged with the rear recompression shock. It remains unclear whether this rarefaction wave at the base of the geometry is accurate, as discussed in Sec. 8.2. For now, the conclusion is that if a more-complex simulation were run, including turbulence effects, this clear rarefaction wave would either not be present or would merge with the other shocks during propagation. The far-field result would then be an N-wave. Further simulations are required to verify this claim.

For the Falcon-9 geometry, three features also persist at the edge of the computational domain, but the structure is different from the Cylinder case. The front shock comes from the detached bow shock at the bottom of the booster. The rarefaction wave produced at the corner of the base of the geometry is effectively negated by a shock wave produced by the base of the landing legs, as was seen in Sec. 8.2. As also seen in Sec. 8.2, the folded landing legs produce rarefaction waves that merge with a shock wave produced by the grid fins. Such a rarefaction wave produced in the vicinity of the folded landing legs can be seen in near-field simulations by Charbonnier *et al.* (2022). The trend for rarefaction waves to migrate backward in the shock system balances out the trend for the shock wave to migrate forward, producing a balanced central shock. Lastly, similar to the Cylinder case, a recompression shock occurs at the end of the geometry. In the Falcon-9 results, all three major shocks are observed to mutually diverge at the edge of the computational domain, suggesting that the three shocks will persist in the far field. While many of these same near-field flow effects can be seen in the wind-tunnel measurements and simulations of Marwege *et al.* (2022), Charbonnier *et al.* (2022), and Bykerk *et al.* (2022), the relationship between the flow features produced by the

folded landing legs and the grid fins cannot be easily deduced either because their models did not include grid fins or their results did not contain details far from the model. Nevertheless, the fact that similar near-field flow structures are found in the literature substantiate the claim that the simulations in this chapter, although simplified, are sufficiently accurate for studying much of the overall flow field. The conclusion of this section is the same as Sec. 8.2, that the central shock in the triple boom is due to a forward-migrating shock from the grid fins merging with a rearward-migrating rarefaction wave produced by the lower portions of the booster, including the folded landing legs.

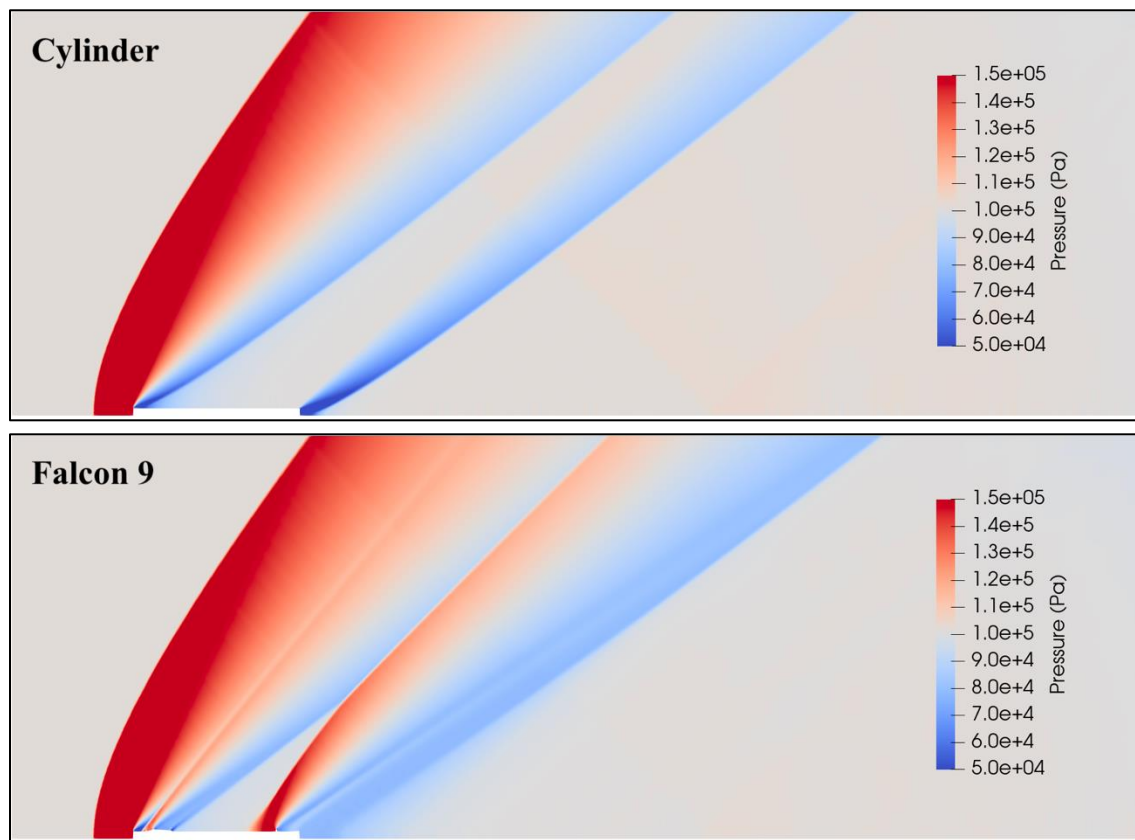


Figure 8.4 Computational fluid dynamics simulations for both the Cylinder and Falcon-9 geometries in the near field. The simulations were run at Mach 1.5. The computational domain for each was 280×100 m.

8.4 Method C: Photographic Evidence

The final piece of evidence to determine the triple-boom origin comes from a unique photograph taken during the SpaceX NG-21 mission. While this analysis is not as technically rigorous, it presents a unique way to validate the results in Secs. 8.2 and 8.3. The original photograph is

shown in Fig. 8.5(a). Condensation clouds form in regions of low pressure, where the conditions temporarily permit water in the air to condense (Campbell and Chambers, 1994). While the shocks themselves are not visible, these condensation clouds highlight important flow features that can help determine approximate shock locations. These features, illustrated in Fig. 8.5(b), point to the same conclusion as Secs. 8.2 and 8.3. Because regions of fluid expansion tend to form between shocks, approximate shock positions can be estimated. First, there must be a detached bow shock in front of the leading edge of the geometry, denoted by the letter “A”. This shock cannot be seen in the photograph, but its presence is inferred because all supersonic bodies have front shocks. Behind this shock, a condensation cloud forms that persists up until the grid fins, where the cloud abruptly becomes less pronounced. This suggests the presence of a strong rarefaction between the bottom of the booster and the grid fins. The sudden change in the local pressure suggests the presence of a shock located at the grid fins, denoted by the letter “B”. Following this, another condensation cloud appears at the top of the booster geometry. This rarefaction is related to the recompression shock (denoted by the letter “C”) expected at the end of all supersonic bodies. The final result is a shock system with three distinct features. Although the shock system drawn here is approximate and represents only the near-field fluid flow, the overall structure agrees with the results found using the other methods in this chapter.

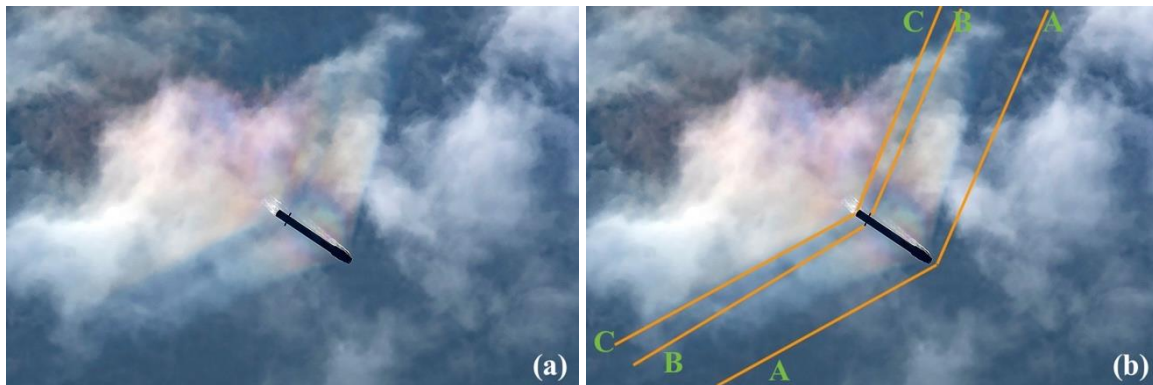


Figure 8.5 (a) Photograph of the descending booster during the NG-21 mission. (b) The same photograph with annotations indicating approximate shock locations. [Photo copyright: Ben Cooper (<https://www.launchphotography.com>). Used with permission.]

8.5 Conclusion

In this chapter, the Falcon-9 triple sonic boom has been explained. The first and third shocks are the typical shock structures expected from a finite body relating to the front and rear of the geometry. The extra, central, shock is formed by a combination of the grid fins and the lower portions of the booster, including the folded landing legs. These lower portions of the booster produce a rarefaction wave that tends to migrate toward the back of the shock system, while the grid fins produce a shock

wave that tends to migrate toward the front of the shock system. When the two structures merge, a balanced shock forms that shows relatively little motion within the signature. The relative strengths of the rarefaction and shock waves determine the location of the final central shock within the sonic boom signature.

This conclusion is reached using three different methods. In the first method, sonic boom theory is used to produce an approximate near-field source function, which is converted to pressure and propagated numerically via the nonlinear acoustic Burgers equation. When the booster is modeled as a simple cylinder, an N-wave is produced in the far field. When the folded landing legs and extended grid fins are included, a triple-boom signature is produced in the far field. The second method uses computational fluid dynamics simulations to visualize the near-field flow around the booster, which agrees with the results in Sec. 8.2. The third method uses a unique photograph taken during a booster flyback where condensation clouds were visible around the booster. The condensation clouds highlight regions of low pressure, which agree well with the other two evidences.

While exciting, more research considering these booster flyback sonic booms needs to be completed. For example, simulations involving turbulent flow are needed to more accurately model the near-field flow around the booster, which could help determine what parts of the vehicle could be used to optimize the sonic boom signature. Although F-function methods can provide quick predictions, their use for blunt rocket boosters during flyback needs to be further validated. We suggest that near-field signatures from wind tunnel testing should be used as inputs into sonic boom propagation software to obtain more-accurate predictions. Lastly, the practical effects on structures, communities, and the environment from having a triple sonic boom should be investigated to determine whether the additional shock produces any extra effects beyond those produced by an N-wave.

Acknowledgments

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We also thank the two anonymous reviewers and the associated editor, whose careful feedback improved and clarified many parts of this chapter.

Chapter 9

Modeling the Falcon-9 Triple Sonic Boom Over a Range of Conditions

Abstract

¹In the age of commercial spaceflight, many organizations are designing rockets for reuse. Most designs employ some form of propulsive landing either on land or at sea. The foremost among these organizations is Space Exploration Technologies Corporation (SpaceX) with their Falcon-9 rocket. As such rockets return, they produce audible sonic booms over the surrounding areas. The Falcon-9 booster's sonic boom signature is unique, consisting of three primary shocks instead of the two associated with traditional N-waves. This provides an opportunity to study sonic boom formation from a unique geometry and to see whether the triple boom can be physically explained. This paper considers F-function and computational fluid dynamics methods to model the booster's sonic boom under conditions ranging from Mach 1.5 to 2.5. Results support the conclusion of Anderson and Gee (2025) [JASA Express Lett. 5, 023601 (2025)] that the central shock is the result of a rearward-migrating rarefaction wave produced by the lower portions of the booster merging with a forward-migrating compression wave produced by the grid fins. Although it is clear that both the grid fins and the lower portions of the booster contribute to the central shock, the different models disagree on their relative importance in producing the final shock.

¹This chapter is derived from a paper published in the conference proceedings of the American Institute of Aeronautics and Astronautics with the following citation:

Anderson, M. C. and Gee, K. L. (2025). "Modeling the SpaceX Falcon-9 Booster's Triple Sonic Boom Using Multiple Models and Conditions," in 30th AIAA/CEAS Aeroacoustics Conference. <https://doi.org/10.2514/6.2025-3081>

The authors retained copyright for the published paper, and the material is reused here as part of this dissertation. Minor changes have been made to fit within the context of this dissertation and to improve clarity and formatting. No conclusions or major results have been changed to the portions that have been previously published. Two additional chapter appendices have been added that do update and clarify some of the conclusions.

9.1 Introduction

As the global launch cadence increases, sonic booms from rockets are becoming increasingly common. Launch vehicles produce sonic booms on ascent and descent (Hilton *et al.*, 1972; Henderson and Hilton, 1974a,b; Maglieri *et al.*, 2011), regardless of whether the descent is controlled or not. Typically, these sonic booms occur over the ocean and seldom impinge on land. However, when a rocket is intentionally flown back to land for reuse, it produces an audible sonic boom on land. These sonic booms, sometimes referred to as “flyback booms” (Anderson *et al.*, 2024c; Anderson and Gee, 2025b), can persist to distances at least as far as 25 km from the landing location (Anderson *et al.*, 2024c) and represent a phenomenon that will become more common as different organizations pursue rocket reusability.

Having landed their Falcon-9 rocket hundreds of times, Space Exploration Technologies Corporation (SpaceX) is the dominant organization producing reusable rockets (SpaceX, 2026). A typical flight profile proceeds as follows (SpaceX, 2023): the two-stage Falcon-9 rocket lifts off using the thrust of nine booster-stage engines. The booster lifts the upper stage and payload high into the atmosphere before separating. While the upper stage and payload continue to orbit, the booster stage either continues to coast downrange to a barge landing or reverses orientation and reignites its engines to travel back to the launch site. After a coast phase lasting a few minutes, while still around 50 km or higher in altitude, the booster ignites 1–3 engines for the “entry burn”, which slows the booster before entering the thicker atmosphere at lower altitudes. Finally, after another brief coast phase, the booster ignites 1–3 engines one more time shortly before extending its landing legs and touching down softly on the landing pad.

While NASA and other agencies have studied the effects of traditional aircraft sonic booms on structures and human response for several decades (Maglieri *et al.*, 2014), little research has been performed on these rocket flyback sonic booms. Aside from initial data collection and analysis efforts (Durrant *et al.*, 2022a, 2023; Anderson and Gee, 2024; Anderson *et al.*, 2024c), another important step is to attempt physics-based modeling of the unique features of these sonic booms. For example, while most sonic booms tend toward N-wave shapes (with two shocks) (Maglieri *et al.*, 2014), Falcon 9 flyback sonic booms tend toward a triple-boom signature with three primary shocks (Anderson *et al.*, 2024c). The three shocks show little to no sign of evolution toward an N-wave, and the total sonic boom duration remains nearly constant at all distances from the landing location (Anderson *et al.*, 2024c; Anderson and Gee, 2024). Although sonic boom signatures with three primary shocks have been measured before (see several examples in (Maglieri *et al.*, 2014)), ensuring that the reasons for the Falcon 9 booster’s triple sonic boom are understood can provide insight into future flyback boom predictions. For example, it is already known that the SpaceX Starship Super Heavy booster also produces a triple sonic boom (Gee *et al.*, 2024b). Understanding the physics can help determine whether this is a universal feature expected from all rocket flyback events.

Recent work by Anderson and Gee (2025b) indicates that the triple-boom signature is a direct consequence of the booster’s geometry. Using Whitham’s F-function paired with numerical propagation via the Burgers equation, they show that the center shock can be explained as the product of a forward-traveling shock wave produced by the grid fins and a backward-traveling shock

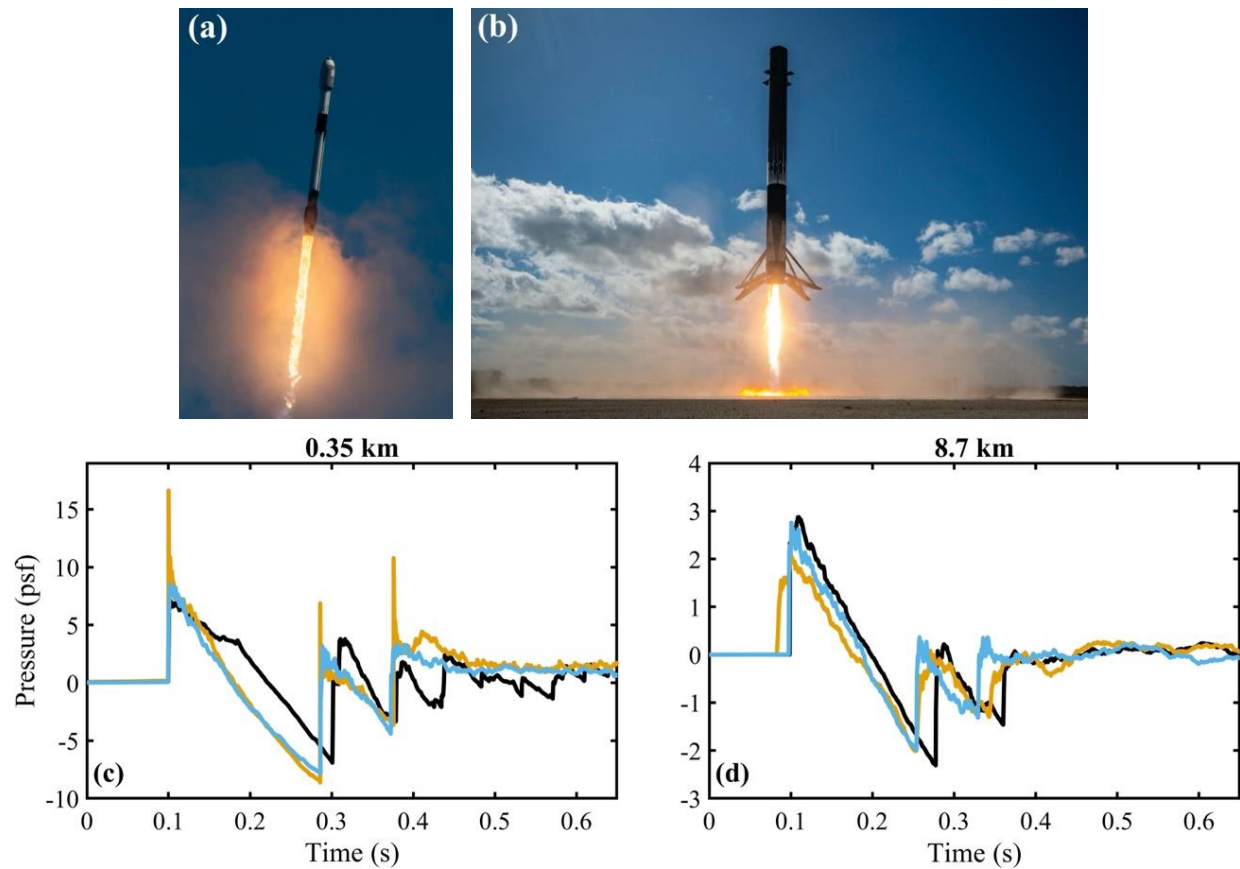


Figure 9.1 (a) A full Falcon-9 rocket shortly after liftoff. (b) A Falcon-9 booster moments before a successful landing. (c) Sonic boom waveforms measured 0.35 km away from the landing pad during three different missions. (d) Sonic boom waveforms measured 8.7 km away from the landing pad during the same three missions. [This entire figure is reproduced from Anderson and Gee (2025b) without changes (CC BY-NC 4.0 DEED License). Credit for photographs (a) and (b): SpaceX (CC BY-NC 2.0 DEED License. No changes made).]

produced by rarefaction waves near the base of the booster, including the folded landing legs. The resultant shock is more balanced and does not migrate as rapidly to merge with either the front or rear shocks. The calculations were carried out using both a plain cylinder of equal proportions to the booster and a cylinder with protrusions representing the folded landing legs and the grid fins. While the plain cylindrical geometry produced a signature that ultimately evolved into an N-wave, the signature from the more-realistic geometry became a triple boom in the far field. Simple computational fluid dynamics (CFD) simulations and photographic evidence shown in Anderson and Gee (2025b) support the results from the Whitham-Burgers approach.

The goal of this chapter is to expand on the work of Anderson and Gee (2025b) and this chapter proceeds as follows. In Sec. 9.2, the near-field pressure signatures are estimated using F-function

and CFD approaches. The propagation modeling is discussed in Sec. 9.3. In Sec. 9.4, the near-field signatures are propagated to the far field. Section 9.5 then contains a summary of the conclusions found in this chapter. Two appendices are also included that contain more CFD results and a validation case for the propagation code.

9.2 Determining Near-field Pressures

The Falcon-9 booster shows little similarity to traditional aircraft. A schematic is provided in Fig. 9.2, indicating some unique geometrical aspects of this vehicle. As the vehicle descends, its engine section faces the oncoming flow. The grid fins near the top of the booster also represent a unique flow feature not seen on traditional aircraft. These grid fins are used to control the booster aerodynamically on descent and the flow around and through them is complicated (Charbonnier *et al.*, 2022).

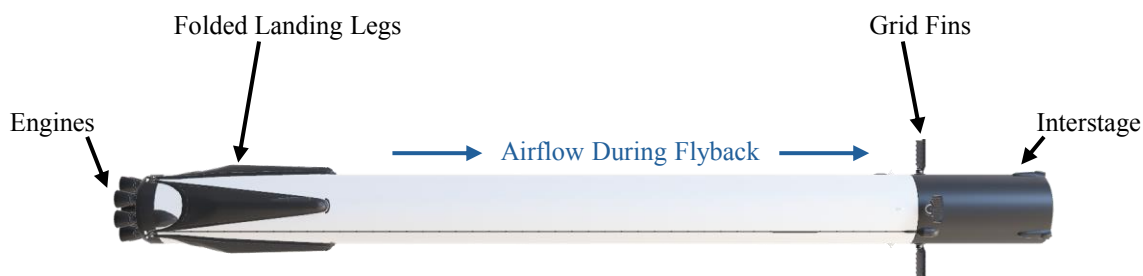


Figure 9.2 A Falcon-9 booster. Important parts of its geometry, along with the airflow direction, are indicated. This figure is reproduced from Anderson and Gee (2025b) without changes (CC BY-NC 4.0 DEED License). The original 3D model comes from Stanley Creative (2023) (CC BY 4.0 DEED License. Changes made.).

In this section, approximate near-field pressure distributions are obtained via the Whitham F-function (Maglieri *et al.*, 2014; Whitham, 1952) and CFD. Each has trade-offs. The Whitham F-function assumes first order flow details, which is unlikely to be strictly accurate for such a blunt geometry. Meanwhile, due to the prohibitively high cost of three-dimensional simulations under the resources allotted to the current analysis, the CFD models are two-dimensional and do not capture the full three-dimensional flow field. Nevertheless, it is assumed that these methods all produce near-field pressure distributions that are sufficient to permit a study of the overall waveform shape, though the shock amplitudes and exact positions are not expected to be perfectly accurate. It is strongly recommended that future wind-tunnel tests and three-dimensional CFD simulations be used to determine the full pressure distribution around the booster. Similar tests have been performed before (Bykerk *et al.*, 2022; Marwege *et al.*, 2019; Charbonnier *et al.*, 2022), but the focus was on vehicle loads and not on sonic boom prediction.

9.2.1 Whitham F-function

The first-order theory (Maglieri *et al.*, 2014; Whitham, 1952) for the flow field around a supersonic projectile estimates the pressure field according to

$$\delta p = \frac{p_a \gamma M_\infty^2}{(2\beta r_0)^{1/2}} F(x), \quad (9.1)$$

where δp is the pressure change from ambient, p_a is the ambient pressure, γ is the ratio of specific heats, M_∞ is the free-stream Mach number, β is the quantity $\sqrt{M_\infty^2 - 1}$, r_0 is the distance from the vehicle, and x is the lengthwise location along the geometry. The quantity $F(x)$ is known as the “F-function”, and it represents the specific geometry being modeled. Strictly speaking, the coordinate x should be replaced with $\chi = x - \beta r_0$, but it is assumed that $\chi \approx x$ for the current analysis because blunt objects tend to produce shocks that do not initially propagate along the far-field Mach lines (Carlson and Mack, 1977).

Modifications to the Booster’s Blunt Geometry

Although F-function methods were originally developed for use with slender bodies, Carlson and Mack (1977) noted that the slender-body theory still tends to work well when applied to blunt geometries for the purpose of sonic boom prediction. To further improve predictions, methods proposed by Gottlieb and Ritzel (1988) are applied in this chapter to improve shock placement around the blunt geometries.

The Falcon-9 booster has three primary blunt features: the bottom where the engines are located, the grid fins jutting out from the side of the booster, and the top of the booster where the geometry abruptly terminates. As for any supersonic blunt body, a detached bow shock is expected at the base of the booster. To account for the standoff distance between the shock and the body of the booster, an artificial body extension is added to the bottom, ensuring that the shock occurs at the proper location. This extension can be represented by a cubic polynomial

$$g(x) = ax^3 + bx^2 + cx + d, \quad (9.2)$$

subject to boundary conditions. At the tip of the extension, the extension radius (R_0) goes to zero and the slope goes to

$$R'_0 = \beta \left(\frac{3(\gamma + 1)^2}{4M_\infty^2} \right)^{-1/4}. \quad (9.3)$$

However, this produces a new tip that still exceeded the bluntness criteria used by Gottlieb and Ritzel (1988). Therefore, a later definition in Gottlieb and Ritzel (1988), designed for blunt features along the body, was used and found to produce a tip that was closer to meeting the bluntness criteria. This definition is

$$R'_0 = \frac{2}{\gamma + 1} \frac{\beta^2}{M_\infty^2}. \quad (9.4)$$

This definition of R'_0 was used to produce new effective tips for the blunt geometries. Additionally, the extension must match the radius (R_1) and slope (R'_1) of the booster body where it joins the booster. The final constraint is that the extension must be of length

$$\Delta x = \frac{3R_1}{2R'_0 + R'_1}, \quad (9.5)$$

which is then converted into a coordinate for the tip of the extension (x_0). Lastly, the extension base should be located at the same location as the bottom of the booster (x_1). With all of these conditions in place, the cubic polynomial coefficients representing the extension can be solved for via

$$\begin{bmatrix} x_0^3 & x_0^2 & x_0 & 1 \\ 3x_0^2 & 2x_0 & 1 & 0 \\ x_1^3 & x_1^2 & x_1 & 1 \\ 3x_1^2 & 2x_1 & 1 & 0 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \\ d \end{bmatrix} = \begin{bmatrix} R_0 \\ R'_0 \\ R_1 \\ R'_1 \end{bmatrix}. \quad (9.6)$$

For blunt features that occur after the front of the geometry (like the grid fins on the booster), the process is largely the same, with a few small changes. The required slope at the point where the extension touches the body is calculated via Eq. (9.4) and the standoff distance is

$$\Delta x = \frac{3(R_1 - R_0)}{2R'_0 + R'_1}, \quad (9.7)$$

which is then converted into the coordinate x_0 . The grid fins in this chapter are modeled exactly as in Anderson and Gee (2025b), treating the grid fins as smaller protuberances to allow airflow past them while still producing a shock.

For blunt features that face away from the flow, like the top of the booster, a different type of extension is applied to the body. This extension accounts for the flow after the body and the subsequent turbulent wake. The first portion of the extended geometry is a conical shape that gets smaller with distance behind the top of the booster. The initial radius of the cone must match the top of the booster and the length of the cone is

$$L = 2R(1.83 - 0.186M_\infty), \quad (9.8)$$

where R is the radius of the booster. The conical geometry does not come to a point at this distance, but rather reaches a radius of

$$R_w = R(0.950 - 0.150M_\infty), \quad (9.9)$$

where R_w is the radius of the turbulent wake. After this point, the turbulent wake in this chapter is modeled simply as a constant cylindrical body extending behind the booster.

The modified geometries are shown in Fig. 9.3 for (a) a plain cylinder that represents a Falcon-9 booster without landing legs or grid fins and (b) a cylindrical body that contains protrusions representing the booster's folded landing legs and extended grid fins.

Calculating the F-function

The Whitham F-function $F(x)$ is defined as (Whitham, 1952; Maglieri *et al.*, 2014)

$$F(x) = \frac{1}{2\pi} \int_0^x \frac{A''(\bar{x})}{\sqrt{x - \bar{x}}} d\bar{x} \quad (9.10)$$

where $A''(x)$ is the second derivative of the cross-sectional area as a function of distance x along the body. Strictly speaking, the cross-section should be taken along slices at the Mach angle, but Carlson and Mack (1977) suggest that for blunt bodies it may be more appropriate to use slices that are normal to the geometry as the initial shocks around a blunt body tend not to immediately propagate away at the far-field Mach angle. In this chapter, $A''(x)$ is calculated normal to the geometry. The final F-functions are shown in Fig. 9.3.

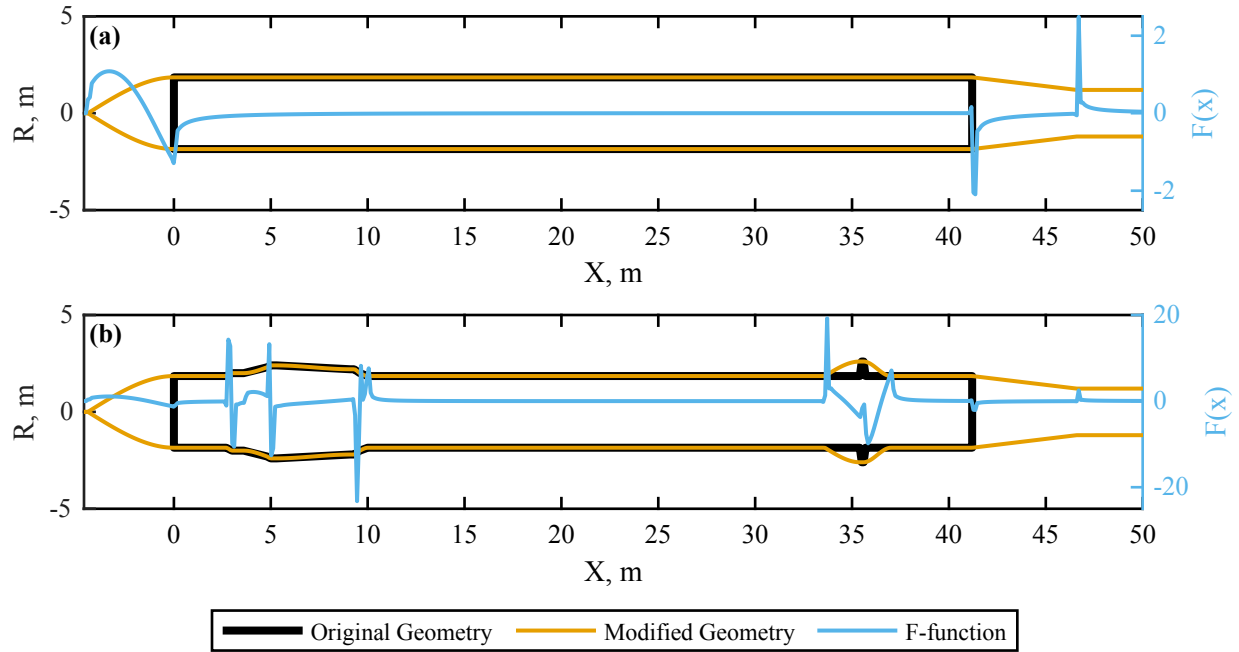


Figure 9.3 The Falcon-9 booster modeled in two levels of detail. (a) The booster modeled as a simple cylinder. (b) The booster modeled as a cylinder with protuberances representing the folded landing legs and the grid fins. The geometry modifications were calculated at Mach 2.0.

The F-functions in Fig. 9.3 are then converted into pressures via Eq. (9.1) (with $r_0 = 41.2$ m) and the results are shown in Fig. 9.4. Immediately, a problem becomes obvious in the predicted pressure magnitudes. The negative pressure magnitudes drop below 1 atmosphere, a phenomenon that is not possible in real fluid flow at an ambient pressure of 1 atm. Additionally, some positive pressure values appear improbably large. This was also noted in Anderson and Gee (2025b), where it was observed that shock formation and decay rapidly decreased these pressure amplitudes to

more-realistic values within the first few meters of propagation. Thus, although further investigation into the physicality of F-function results for descending rocket boosters needs to be performed, it is assumed in this chapter that the propagated results will be good enough for determining the overall waveform shape after propagation. However, the final pressure amplitudes are unlikely to be fully accurate.

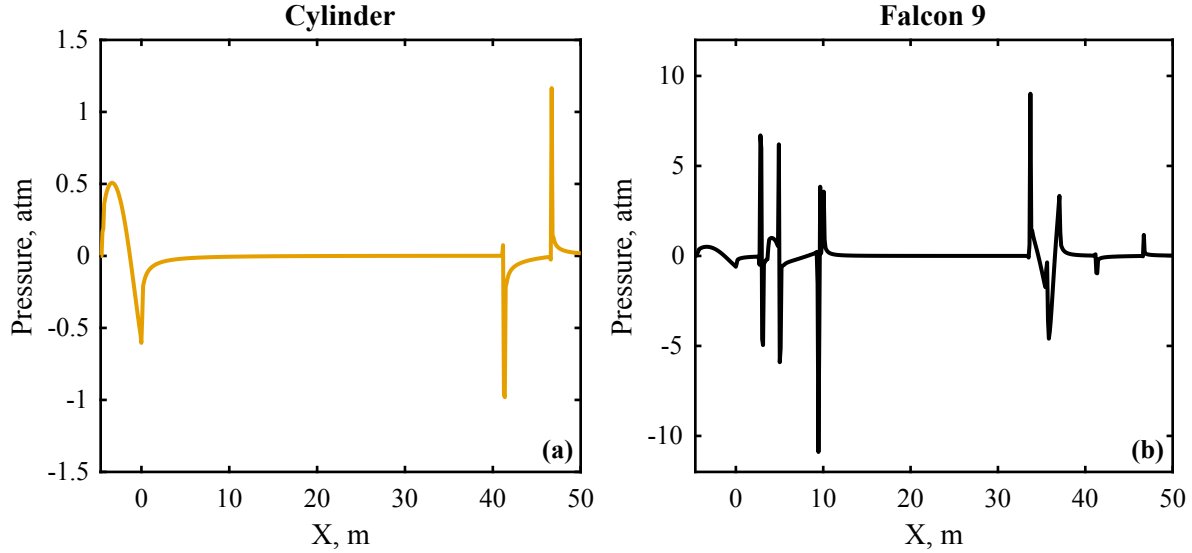


Figure 9.4 The calculated pressures around the (a) Cylinder and (b) Falcon-9 geometries at Mach 2.0 at a linearly-propagated distance of $r_0 = 41.2$ m.

9.2.2 Computational Fluid Dynamics (CFD)

Another method to obtain the pressures in the flow field surrounding a supersonic vehicle is CFD. For the results in this chapter, two-dimensional unstructured meshes for both the Cylinder and Falcon-9 geometries were produced in GMSH (Geuzaine and Remacle, 2024) and the simulations were run in OpenFOAM 11 (OpenFOAM, 2024). The simulations were run with the *shockFluid* solver for compressible flows. Assuming symmetry, the flow was only computed on one side of the geometries, with a *symmetryPlane* boundary condition on the bottom. Further details for each boundary condition are given in Table 9.1. For these simulations, a *k- ω* Shear Stress Transport (SST) turbulence model was used. The initial estimates at the boundaries were solved via the following equations (SimScale, 2025; Direct, 2025):

$$k = \frac{3}{2}(UI)^2, \quad (9.11)$$

$$\omega = \frac{\sqrt{k}}{C_\mu^{1/4} \ell}, \quad (9.12)$$

$$\nu_t = \frac{k}{\omega}, \quad (9.13)$$

where k is the turbulent kinetic energy, U is the freestream velocity, I is the turbulence intensity (taken to be 0.05 throughout this chapter), ω is the specific turbulent dissipation rate, $C_\mu = 0.09$, ℓ is the turbulent length scale (taken to be 0.25 m throughout this chapter), and ν_t is related to the turbulent viscosity. Calculated values are tabulated in Table 9.2 alongside other flow parameters.

Table 9.1 Boundary conditions used in the CFD simulations. The inlet was located on the left boundary and the outlet on the top and right boundaries.

	inlet	outlet	vehicle	bottom
alphat	calculated	waveTransmissive	compressible::alphatWallFunction	symmetryPlane
k	fixedValue	waveTransmissive	kqrWallFunction	symmetryPlane
nut	calculated	waveTransmissive	nutkWallFunction	symmetryPlane
omega	fixedValue	waveTransmissive	omegaWallFunction	symmetryPlane
p	fixedValue	waveTransmissive	zeroGradient	symmetryPlane
T	fixedValue	waveTransmissive	zeroGradient	symmetryPlane
U	fixedValue	waveTransmissive	noSlip	symmetryPlane

Table 9.2 Flow properties for each of the simulations.

	alphat (kg/m s)	k (m ² /s ²)	nut (m ² /s)	omega (1/s)	p (kg/m s ²)	T (K)	U (m/s)
M = 1.5	0	975	4.27	228	1e5	300	(510, 0, 0)
M = 2.0	0	1734	5.70	304	1e5	300	(680, 0, 0)
M = 2.5	0	2709	7.12	380	1e5	300	(850, 0, 0)

There are two main benefits to using CFD to obtain near-field pressures rather than relying on F-function methods. First, blunt portions of the geometry can be modeled directly without needing to make assumptions about shock location and strength. Second, the grid fins can be more appropriately modeled. Meshes for the Cylinder and Falcon-9 geometries are shown in Fig. 9.5, including a close view of the grid fins. The fins are modeled using seven diamond-shaped elements to approximate the number of struts used in the physical grid fins. This approximation allows for a better simulation of the flow through the fins and the shock structure produced by the fins. This is an improvement over what was done in Anderson and Gee (2025b), where the same geometry used for F-function analysis was used in the CFD analysis.

Simulations were run at Mach 1.5, 2.0, and 2.5, and zoomed-in pressure fields shown in Fig. 9.6. In the near field, the Cylinder produces a triple sonic boom consisting of the bow shock followed by a rarefaction wave which steepens into a shock and then ending with the wake shock. This same overall structure is observed at all three Mach numbers. In contrast, the Falcon-9 geometry

produces many more near-field shocks at each Mach number, and those shocks can be seen beginning to coalesce with distance from the booster. While these are zoomed-in results, the full calculated domains can be seen in Chapter Appendix A.

Finally, the CFD results can be used to extract pressures along lines parallel to the geometries. To be thorough, pressures were extracted along three different lines corresponding to different distances from the geometries (10, 20, and 41.2 m). The freestream pressure was then subtracted and the amplitude effects of cylindrical spreading were then approximately accounted for as

$$\delta p = (p - p_\infty) \left(\frac{1.85}{r_0} \right)^{1/2}, \quad (9.14)$$

where 1.85 m is the booster radius and the one-half power corresponds to cylindrical spreading.

The final near-field pressure signatures obtained through the CFD methods are shown in Fig. 9.7. Several similarities and differences can be found between these results and those presented using F-function methods in Fig. 9.4. For example, the pressures here are substantially smaller than those in Fig. 9.4, and the rarefactions are not of comparable amplitude to the compressions, as is the case in Fig. 9.4. However, both the CFD and F-function methods agree that the initial bow shock is followed by a rarefaction wave associated with the airflow turning around the blunt lower portion of the geometry. Such negative pressures following the positive pressures induced by blunt bodies have been observed previously Shrout *et al.* (1971), as well as for cases where the tip is pointed but still has a corner or rounded region afterwards (Carlson *et al.*, 1965; Shrout *et al.*, 1971). As shown in Fig. 9.7, this rarefaction wave tends to migrate rearward at farther propagation distances. In the Falcon 9 case, it merges with a forward-migrating shock produced by the grid fins. In the following sections, nonlinear propagation modeling is employed to determine how these near-field signatures evolve during propagation to the far field.

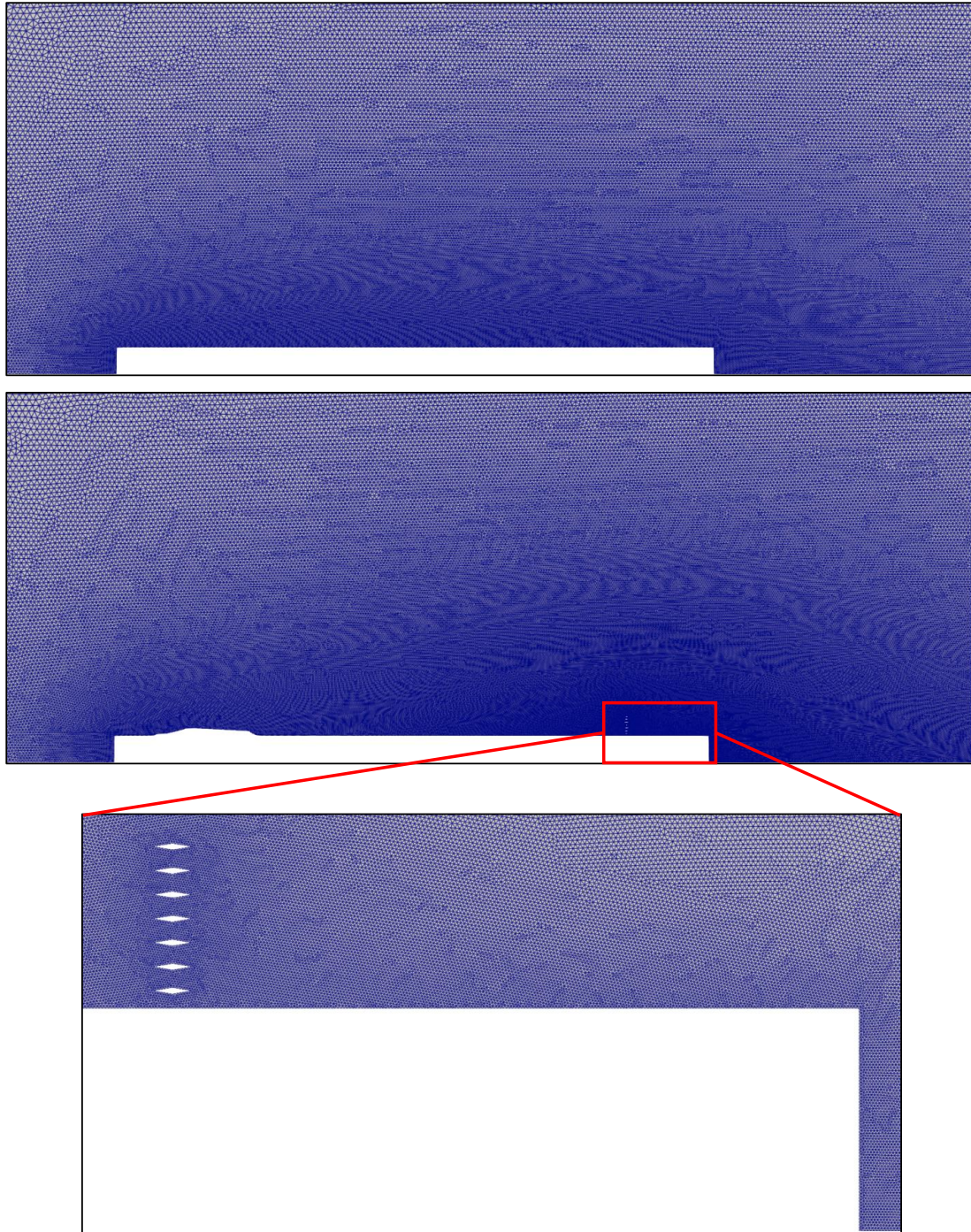


Figure 9.5 Portions of the meshes used throughout the CFD simulations. (Top) the mesh for the Cylinder cases. (Middle) the mesh for the Falcon 9 cases. (Bottom), a closer view of the mesh near the top of the Falcon 9, including the grid fins modeled using narrow diamonds.

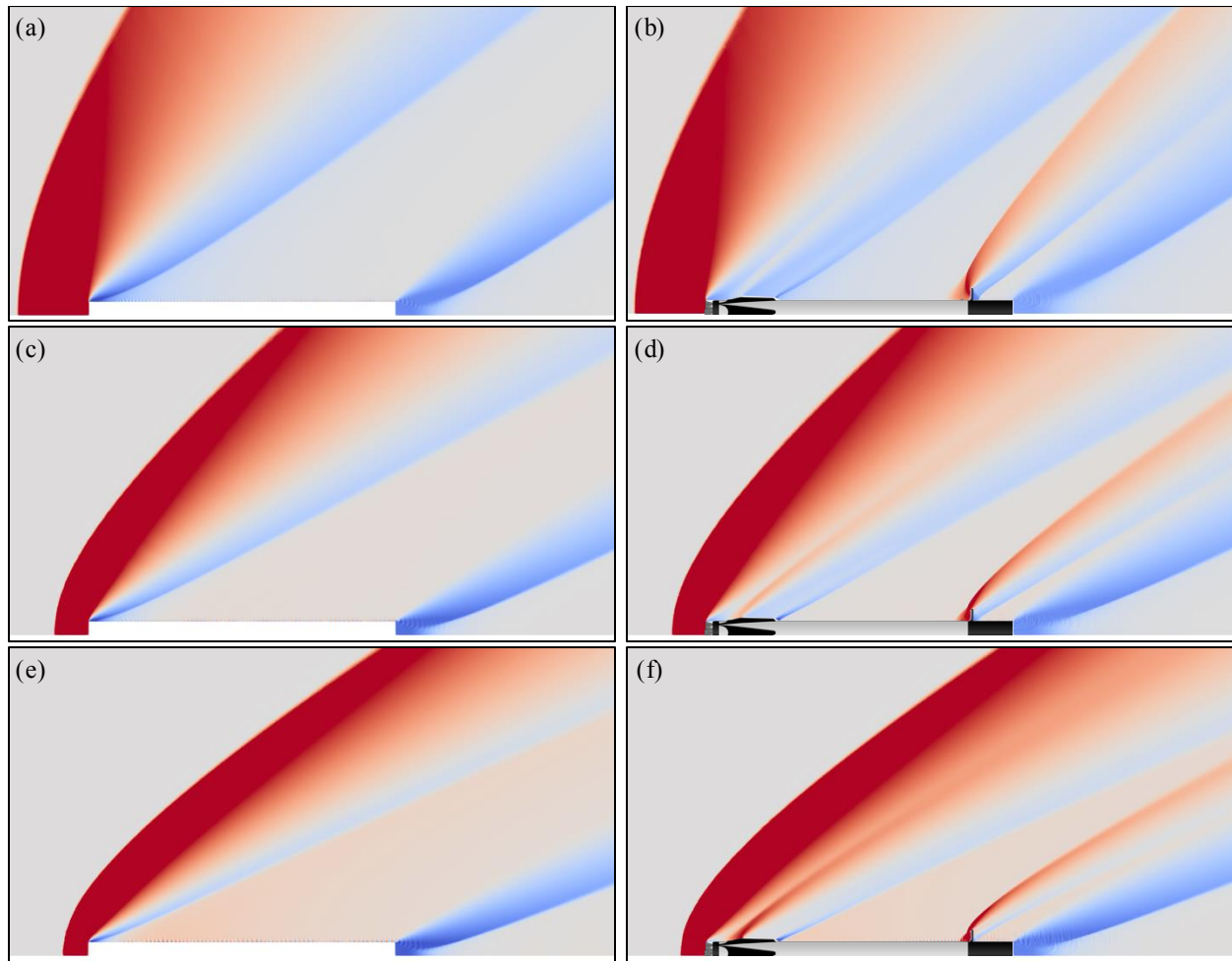


Figure 9.6 Zoomed-in pressure fields for each of the CFD runs. (a) Cylinder, Mach 1.5. (b) Falcon 9, Mach 1.5. (c) Cylinder, Mach 2.0. (d) Falcon 9, Mach 2.0. (e) Cylinder, Mach 2.5. (f) Falcon 9, Mach 2.5. For the Falcon-9 simulations, a model has been superimposed on the results to aid with visualization. The color ranges are from 20 kPa (blue) to 180 kPa (red), with 100 kPa being the freestream pressure.

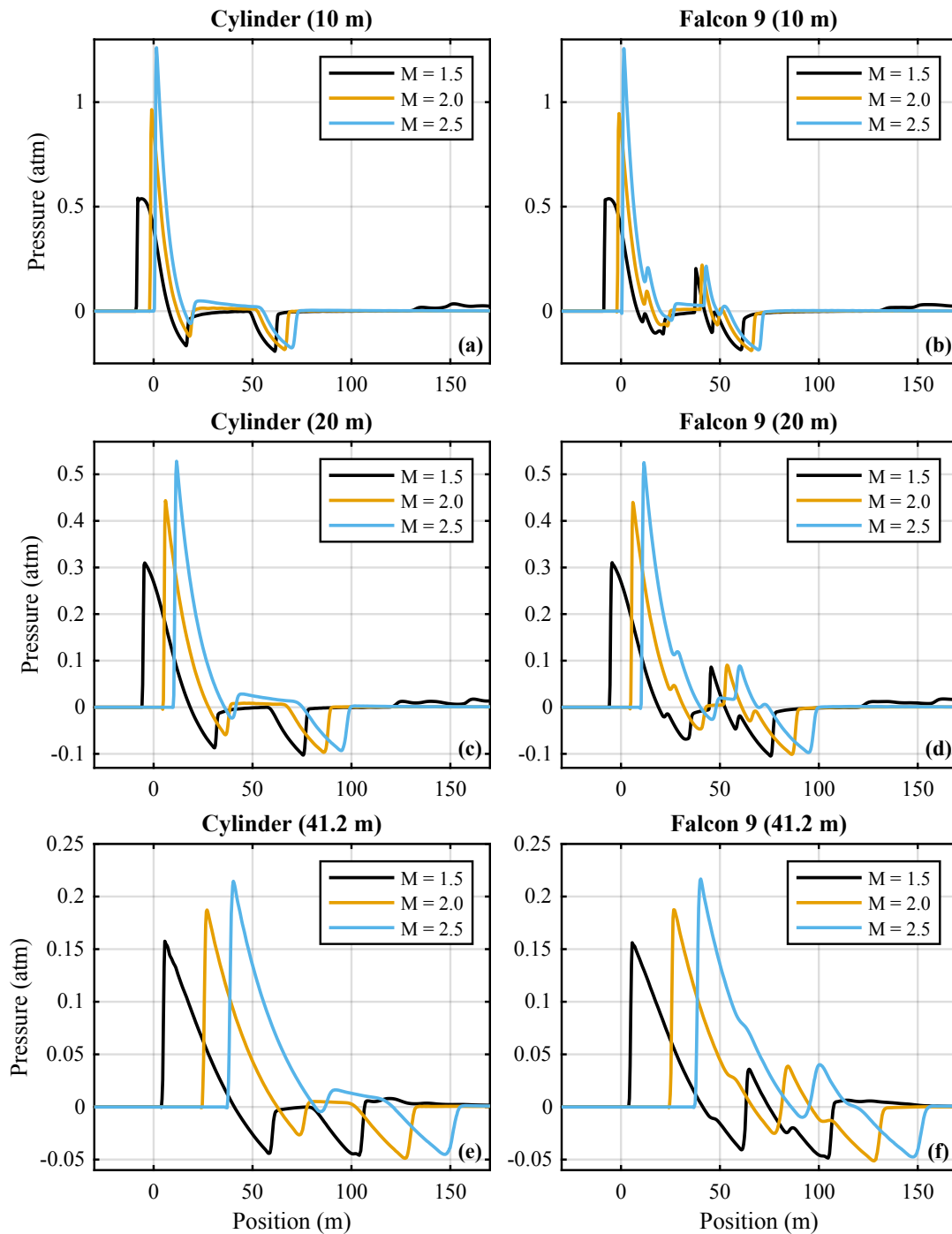


Figure 9.7 The estimated near-field pressure signatures from the CFD simulations across Mach numbers and at three different distances from the geometries. Some extra pressure disturbances after the signatures are visible for the $M = 1.5$ cases. These were caused by minor reflections off the top boundary.

9.3 Propagation Modeling

The Generalized Burgers Equation (GBE) (Hamilton and Blackstock, 2024; Lonzaga *et al.*, 2022) models the effects of nonlinear distortion and can be expressed in lossless form for cylindrically-spreading waves as

$$\frac{\partial p}{\partial r} = \frac{\beta}{2\rho_0 c_0^3} \frac{\partial p^2}{\partial \tau} - \frac{1}{2r} p. \quad (9.15)$$

Here, p is the pressure disturbance, r is the propagation distance, β is the coefficient of nonlinearity taken to be 1.201 in air, ρ_0 is the ambient density, c_0 is the ambient sound speed, and τ is the retarded time. The GBE is commonly used to study sonic boom propagation in modern software packages like PCBoom (Lonzaga *et al.*, 2022). In this chapter, this equation is solved numerically as follows:

1. The shock formation distance is solved for via (Hamilton and Blackstock, 2024)

$$r_{\text{shock}} = \frac{\rho_0 c_0^3}{\beta \frac{dp}{d\tau}|_{\text{max}}}. \quad (9.16)$$

2. The step length is determined by

$$\Delta r = \eta r_{\text{shock}}, \quad (9.17)$$

where $0 < \eta < 1$ is the step size parameter.

3. The waveform distortion is calculated via the Earnshaw solution (Hamilton and Blackstock, 2024),

$$\tau_{\text{distort}} = \tau - \frac{\beta \Delta r}{\rho_0 c_0^3} p. \quad (9.18)$$

4. The waveform is resampled back onto the original time array. This step provides numerical damping, which prevents the formation of discontinuities or triple-values waveforms.
5. The geometric spreading is accounted for by

$$p = \left(\frac{r_{i-1}}{r_i} \right)^{1/2} p. \quad (9.19)$$

6. The process is repeated until the final propagation distance is reached.

To convert the pressure signatures from distance units to time units, the distance units are divided by the assumed ambient sounds speed of 343 m/s and the waveforms are resampled to 20 kHz. Additionally, the time units are then divided by the freestream Mach number M_∞ , which models the fact that in the far field the waves propagate normal to the shock fronts and not parallel to the source geometry.

9.4 Results

The near-field pressures obtained in Sec. 9.2 were propagated using the nonlinear propagation algorithm detailed in Sec. 9.3. The results using the F-function approach are shown in Fig. 9.8. The near-field pressures were calculated at three different Mach numbers (1.5, 2.0, and 2.5) and propagated to four different distances (0.5, 4.0, 10, and 30 km), enabling a comparison across a range of initial conditions and propagation lengths. Across all considered conditions, the F-function approach predicts that the Falcon 9 geometry will produce a triple sonic boom. There is a trend for the central shock to be located closer to the first shock as Mach number increases. Meanwhile, the Cylinder geometry is predicted to produce a triple sonic boom at closer distances and lower Mach numbers. For farther distances and higher Mach numbers, the Cylinder predictions tend toward N-waves.

The results from propagating the CFD near-field signatures are shown in Fig. 9.9 using the same format as Fig. 9.8. The input pressure signatures were the ones at 41.2 m in Fig. 9.7. According to the CFD results, both the Cylinder and Falcon-9 geometries are expected to produce a triple sonic boom at all distances and across all three Mach numbers. As a general trend, the Falcon-9 geometry produces a central shock that occurs shortly before the central shock predicted for the Cylinder. This is due to the forward-migrating shock originating from the grid fins merging with the rearward-migrating rarefaction wave produced near the base of the geometry. This merging tends to slow down the overall migration of the central shock to either the front or the back of the waveform.

To increase confidence that the CFD results are physically meaningful, Fig. 9.10 compares a CFD prediction ($M = 1.5$, $r = 10$ km) with three representative measured signatures at 8 km away from the landing pad for three different missions. Although the central shock's amplitude is smaller in the simulated results than the measured results, its relative position within the waveform agrees well. Additionally, in both the simulated and measured waveforms, there is a small shock occurring shortly before the larger third shock. According to the CFD results, this small shock is produced by a rarefaction wave formed after the air flows through the grid fins and is observable in Fig. 9.6. This same feature is also seen in the laminar CFD simulations in Anderson and Gee (2025b) and was discussed as possibly originating from the grid fins by Durrant *et al.* (2022a). Thus, it is concluded that the origin of this small shock is the rarefaction wave produced after the air flows through the grid fins. The forward-migrating shock wave produced just ahead of the grid fins merges into the central shock (increasing the central shock's amplitude some amount) while the rarefaction wave produced just behind the grid fins fails to merge with the rear shock by 8–10 km of propagation. Thus, it is concluded that the grid fins produce a forward-migrating shock wave that contributes to the far-field central shock and a rarefaction wave that can form a small minor shock before the rear shock in the final signature.

It is also important to note the discrepancy in pressure amplitude between the simulated and measured results. The measured signatures (Fig. 9.10(b-d)) were subject to pressure doubling due to the measurements being made on the ground, while the simulated signature (Fig. 9.10(a)) is free field. Were the simulated waveform to be measured on the ground (and thus experience pressure doubling) the pressures would be about seven times as great as those actually measured. Thus, although the overall waveform shapes appear to be accurate, the pressures are not.

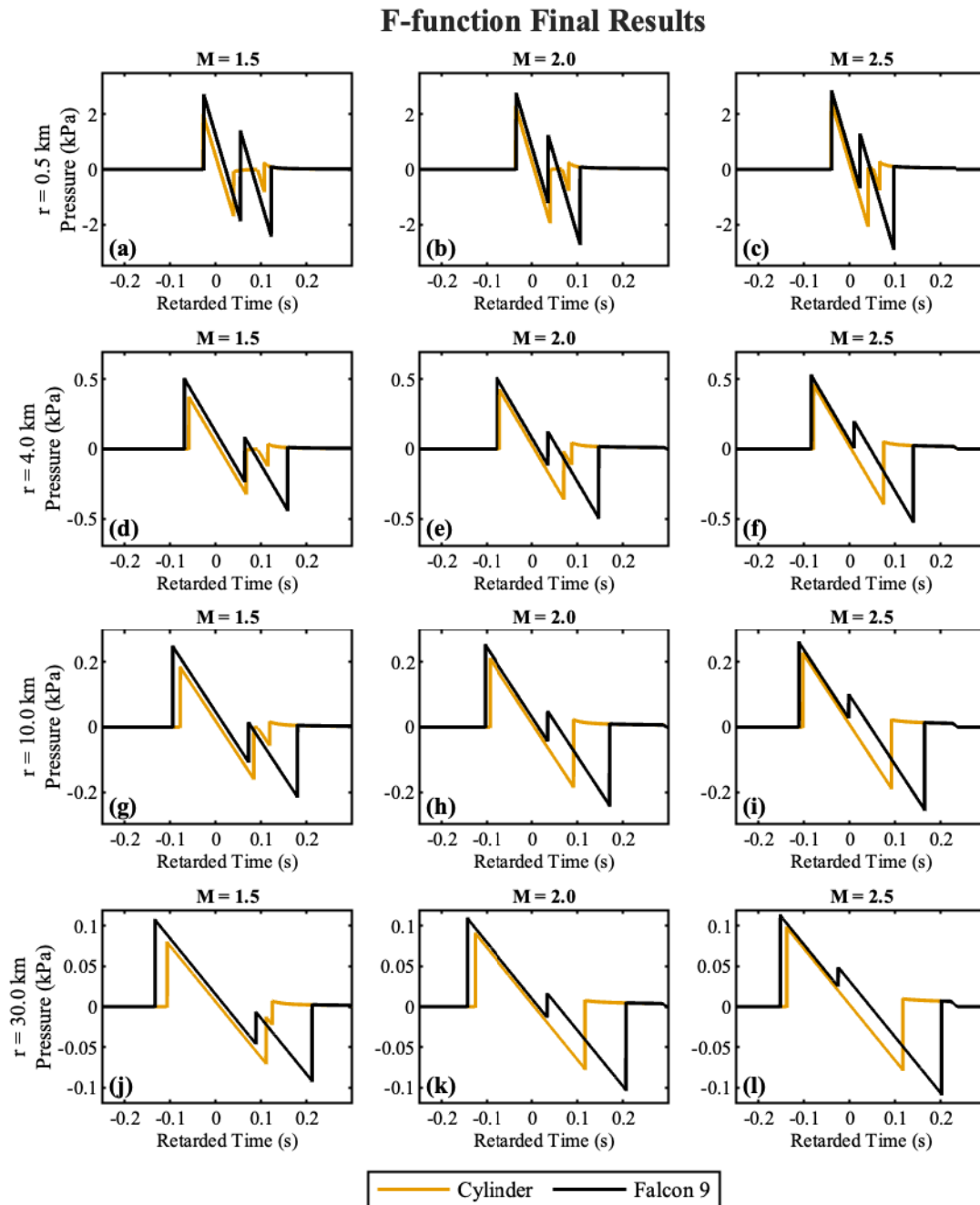


Figure 9.8 Propagated signatures using the Whitham F-function as input. The Mach number is constant within columns and distance increases between rows.

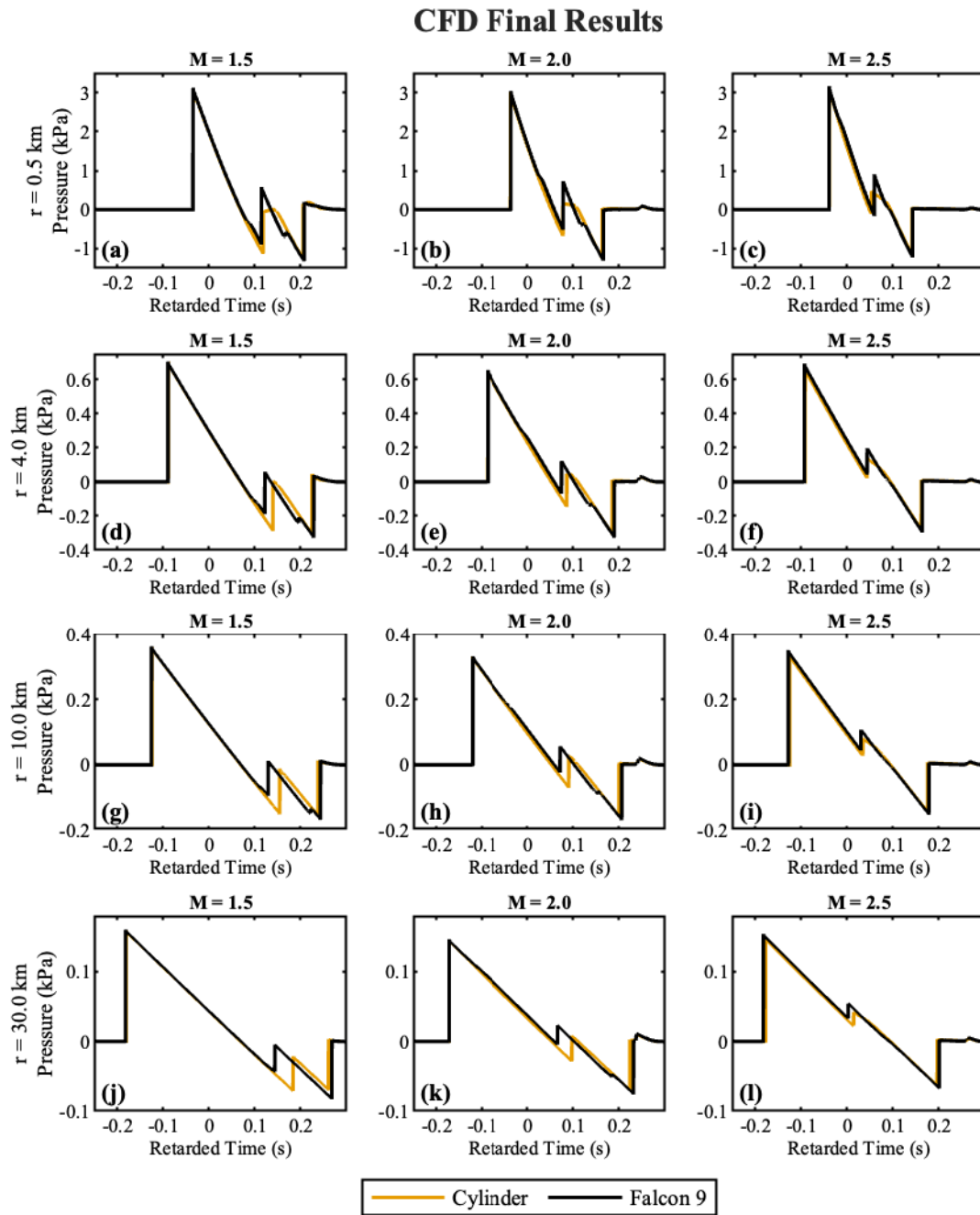


Figure 9.9 Propagated signatures using the CFD results at $r_0 = 41.2$ m with the booster used as input. The Mach number is constant within columns and distance increases between rows.

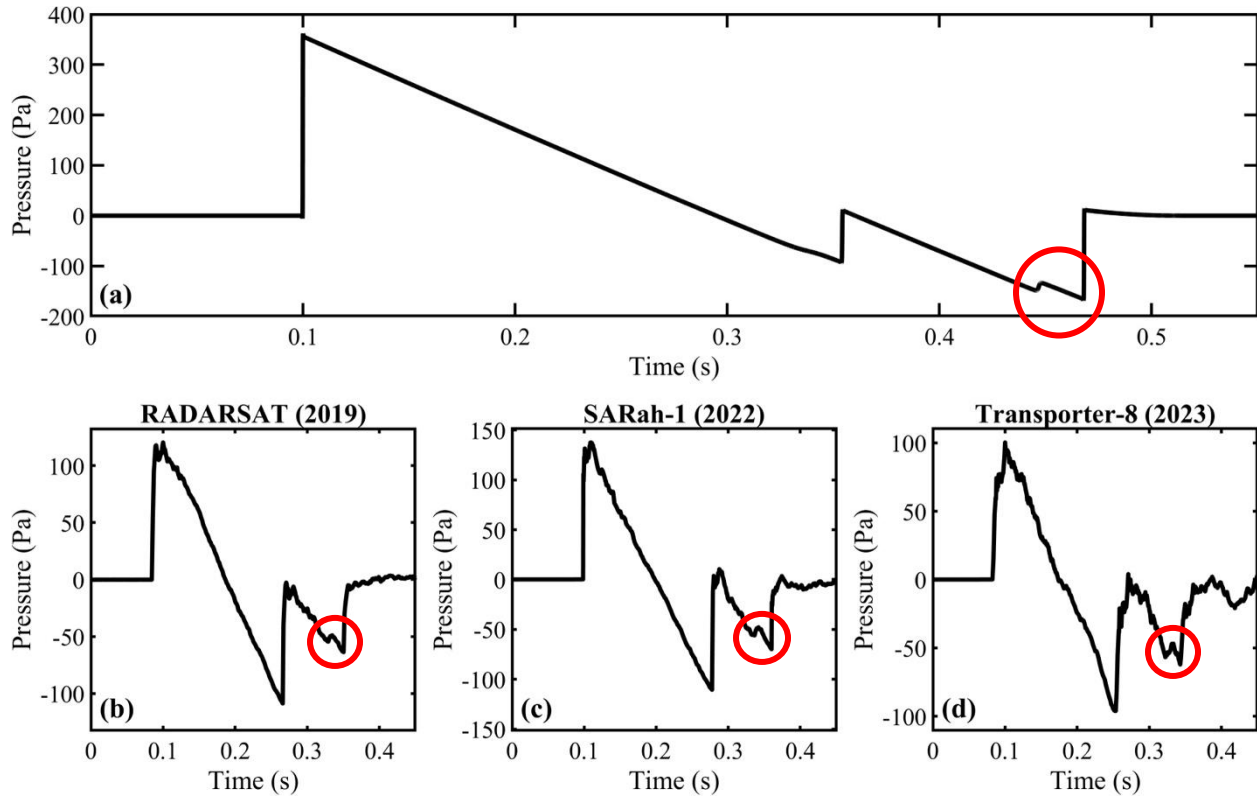


Figure 9.10 Comparison between the CFD results and measurements around 10 km.

While it is clear that the grid fins produce a compression wave and the lower parts of the booster produce a rarefaction wave, it is not clear which dominates the formation of the central shock or if they both contribute equally. The reason this is not clear is that the F-function and CFD methods, which both have pros and cons as discussed in Sec. 9.2, disagree on the relative importance of these two features. The F-function method indicates that the grid fins are required to produce the triple boom. However, the CFD method suggests that while the grid fins play a role in determining the final central shock location and amplitude, they may not be required for producing a triple boom. The true physical answer likely lies somewhere between the results from the F-function and CFD methods.

9.5 Conclusion

While most sonic booms tend toward N-waves with two shocks, flyback sonic booms from Falcon 9 rocket boosters have a triple sonic boom signature. Measured data (Anderson *et al.*, 2024c) show that these triple sonic booms persist out to at least 25 km. These triple sonic booms are not fully modeled in current environmental assessments, where N-wave methods are used to predict sonic boom levels (Anderson and Gee, 2024; Anderson *et al.*, 2024c). Previous work (Anderson and

Gee, 2025b) describes the extra, central, shock as being a combination of a rarefaction wave from the base of the vehicle and a shock wave from the grid fins. The purpose of the analyses in the present paper are to expand on the work of Anderson and Gee (2025b) and include a broader range of conditions and propagation distances.

In this chapter, near-field source functions are generated via the Whitham F-function (Whitham, 1952) and computational fluid dynamics (CFD). These near-field signatures are then propagated via the nonlinear generalized Burgers equation (GBE) out to distances as far as 30 km. The GBE propagation code was validated against an analytical solution for an N-wave and showed agreement within 2% for peak overpressure and shock location (see Chapter Appendix B).

Two approximate geometrical models for the Falcon-9 booster were used throughout the analyses. The lower-fidelity model represents the booster as a simple “Cylinder”. The higher-fidelity model, referred to as the “Falcon 9”, included protrusions for the folded landing legs and grid fins. In the F-function method, the grid fins were also modeled as a small protrusion that allowed air to flow past while still producing a shock. In the CFD method, the grid fins were modeled as several thin diamond airfoils roughly approximating the number of struts used by the physical grid fins. This allows a more realistic approximation to the flow behavior through the grid fins.

Both the F-function and CFD methods, after propagation, predict that the Falcon-9 booster should produce a triple sonic boom. The lower portions of the geometry (i.e., the base of the rocket and the folded landing legs) produce a rarefaction wave that tends to migrate backward in the waveform during propagation. The grid fins produce a forward-migrating shock wave. These two features merge toward the middle of the waveform and account for the central shock. This agrees with the conclusion in Anderson and Gee (2025b).

However, the results become more complicated for the Cylinder. The F-function method predicts that the rarefaction produced by the base of the geometry is sufficiently strong to migrate backward and fully merge with the tail shock. On the other hand, the CFD results predict that this same rarefaction wave has a lower amplitude and is not sufficiently strong to migrate fully toward the rear of the waveform and merge with the tail shock. Thus the CFD near-field signature, after propagation via the GBE, predicts a triple sonic boom for both the Cylinder and Falcon-9 geometries.

The final conclusions of this chapter can be summarized as follows. The first shock in the triple-boom signature is the bow shock expected at the front of all supersonic bodies. The second shock is a combination of a rearward-migrating rarefaction wave produced at the base of the geometry and a forward-migrating shock wave produced by the grid fins. The relative importance of the rarefaction wave and the shock wave is an open question because their strengths vary between the F-function and two-dimensional CFD results. The final shock is the tail or “wake” shock produced at the top of the geometry. Additionally, a minor shock often appears shortly before the final shock in measured data. This shock is successfully modeled in the CFD results as being produced by a rarefaction occurring after the flow passes through the grid fins.

While these results validate several findings in Anderson and Gee (2025b), there remains much work to be done in the emerging field of flyback sonic booms from reusable rockets. The current results suggest that a triple sonic boom could be produced even without grid fins (see Chapter Appendices C and D), something that could be validated by studying sonic booms produced by rocket boosters with less obtrusive fin designs (e.g., Blue Origin’s New Glenn rocket and RocketLab’s

Neutron rocket). If a deep enough understanding of the physics behind these rocket flyback sonic booms is developed, then perhaps design changes could be incorporated to optimize the boom shape. Additionally, all this research has assumed the vehicle axis is perfectly aligned with the freestream, while actual rocket boosters tend to be angled somewhat relative to the freestream. Thus, the effects of breaking the axisymmetry assumption need to be studied, including the effects of lift. Finally, the effects of having three primary shocks vs an N-wave have not yet been studied on structures, wildlife, or communities.

Acknowledgments

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9.6 Chapter Appendix A: Further CFD Results

The zoomed-in CFD results shown in Sec. 9.2 enable a better view of the flow near the vehicle. It is also useful to see the flow throughout the entire domain. This can help validate the propagation results from a qualitative perspective, as the shock coalescence can also be observed in the computational domain for the CFD calculations. The full-domain results for the Cylinder are shown in Fig. 9.11 and the same results for the Falcon 9 are shown in Fig. 9.12. In all cases, the top boundary failed to perfectly transmit waves, and so partial reflections are visible. In some cases throughout this chapter, especially at lower Mach numbers, these reflections are visible in the signatures (e.g., Fig. 9.7 at Mach 1.5 and Fig. 9.9(b)). Of course, these minor pressure disturbances after the sonic boom are not physical.

In Sec. 9.4, only the pressures along the line parallel to and 41.2 m from the geometries were used for propagation. For completeness, Fig. 9.13 shows the results for propagating the Falcon-9 near-field pressures at 10, 20, and 41.2 m to the same four propagation distances shown in Sec. 9.4. Although there is some dependence on which initial distance is chosen, the results remain qualitatively the same, without any change to the final conclusions in this chapter. Although not shown, the results using the Cylinder simulations are also qualitatively the same when using different input distances.

It is important to also note that the propagation model assumes “weak” shocks, in which the pressure excursions are an order of magnitude less than ambient pressure (Hamilton and Blackstock, 2024). Extracting the signature farther from the geometry tends to better meet this assumption, with the caveat that the simulations are two-dimensional and shock coalescence in two dimensions will

occur faster than in a three-dimensional case. Strong shock extrapolation methods like those used in Hicks *et al.* (1972b) and Garcia *et al.* (1973) could be employed in the future to further improve the final signatures.

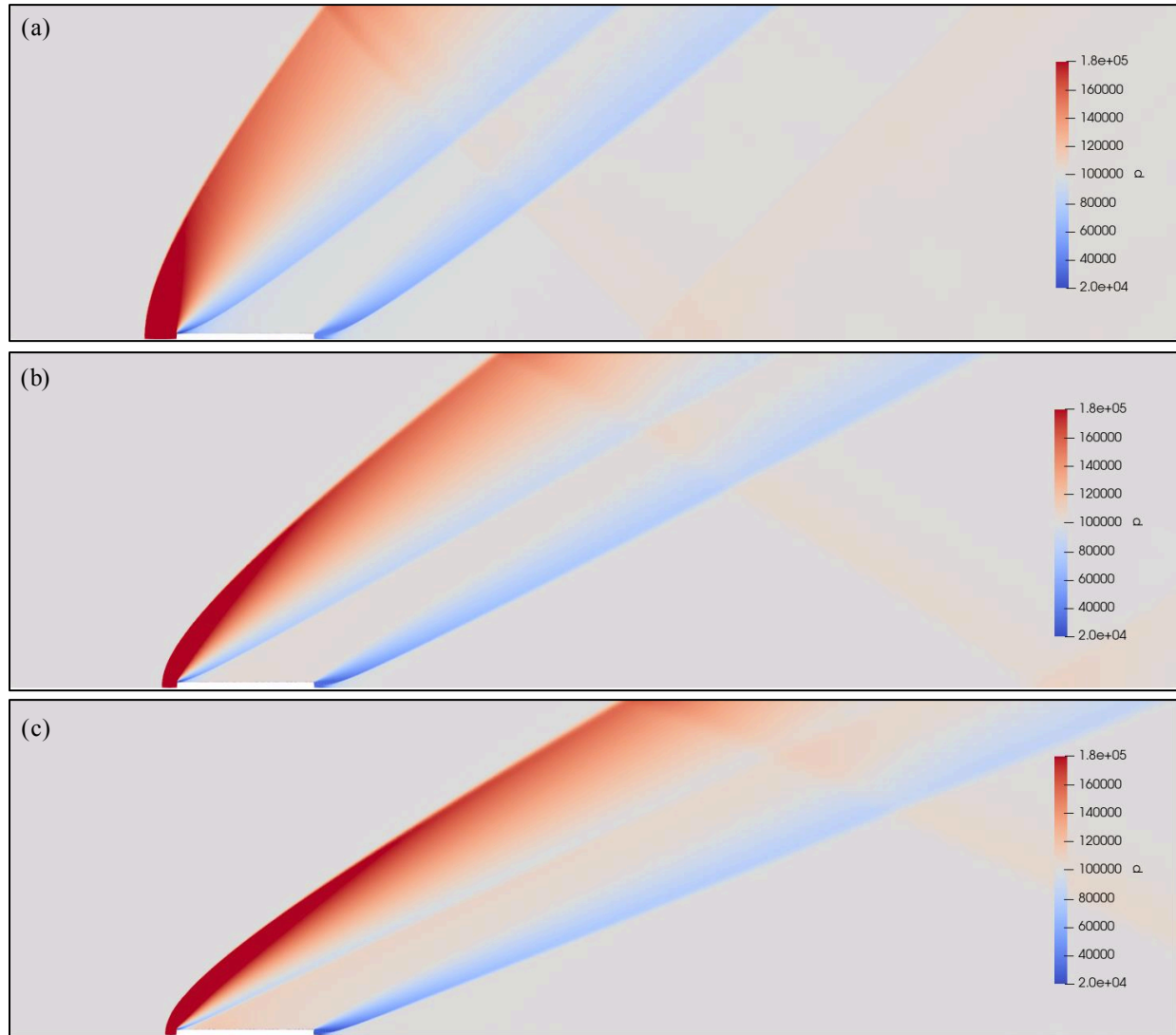


Figure 9.11 CFD results for the Cylinder over the full computational domain at (a) Mach 1.5, (b) Mach 2.0, and (c) Mach 2.5.

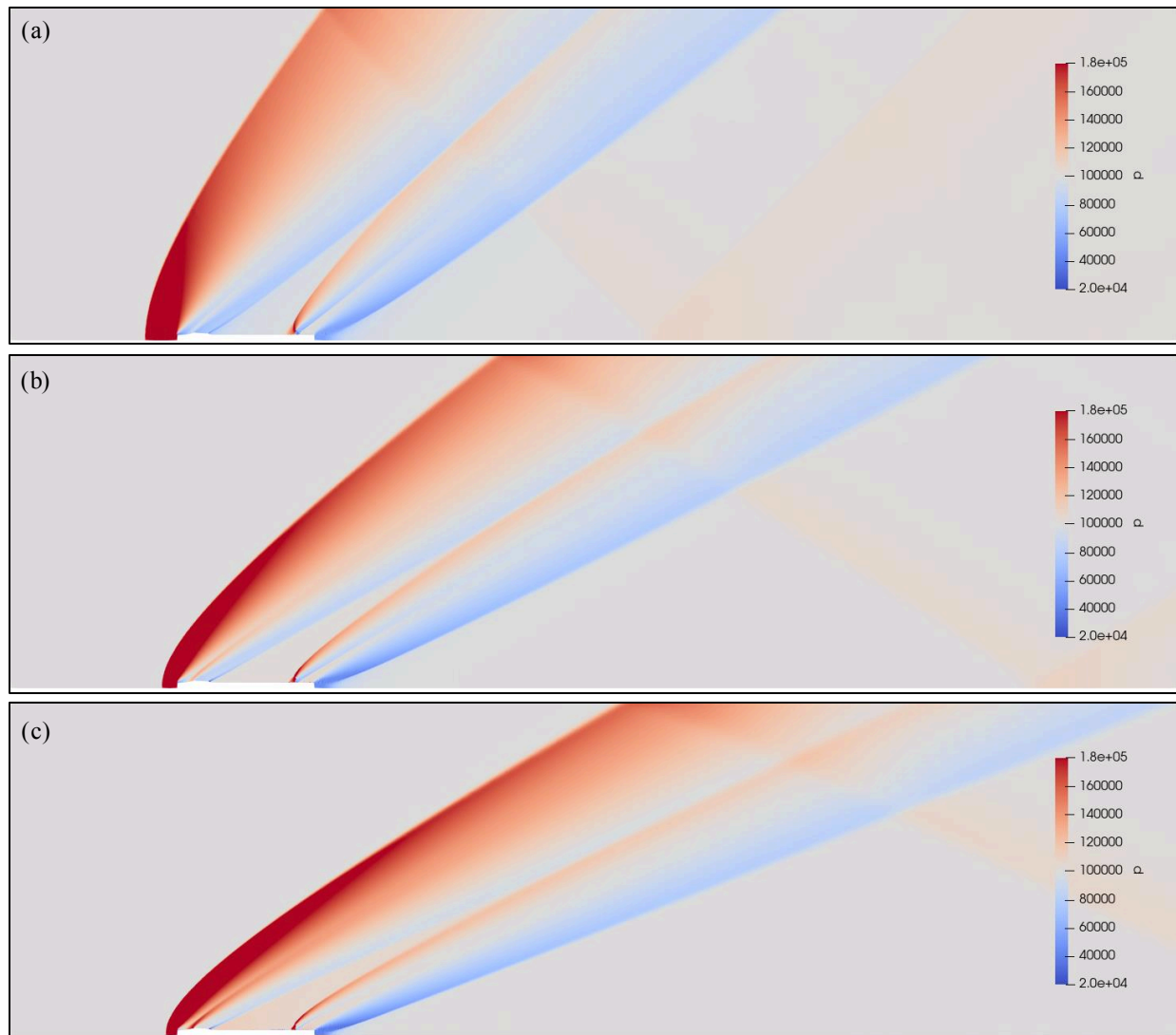


Figure 9.12 CFD results for the Falcon 9 over the full computational domain at (a) Mach 1.5, (b) Mach 2.0, and (c) Mach 2.5.

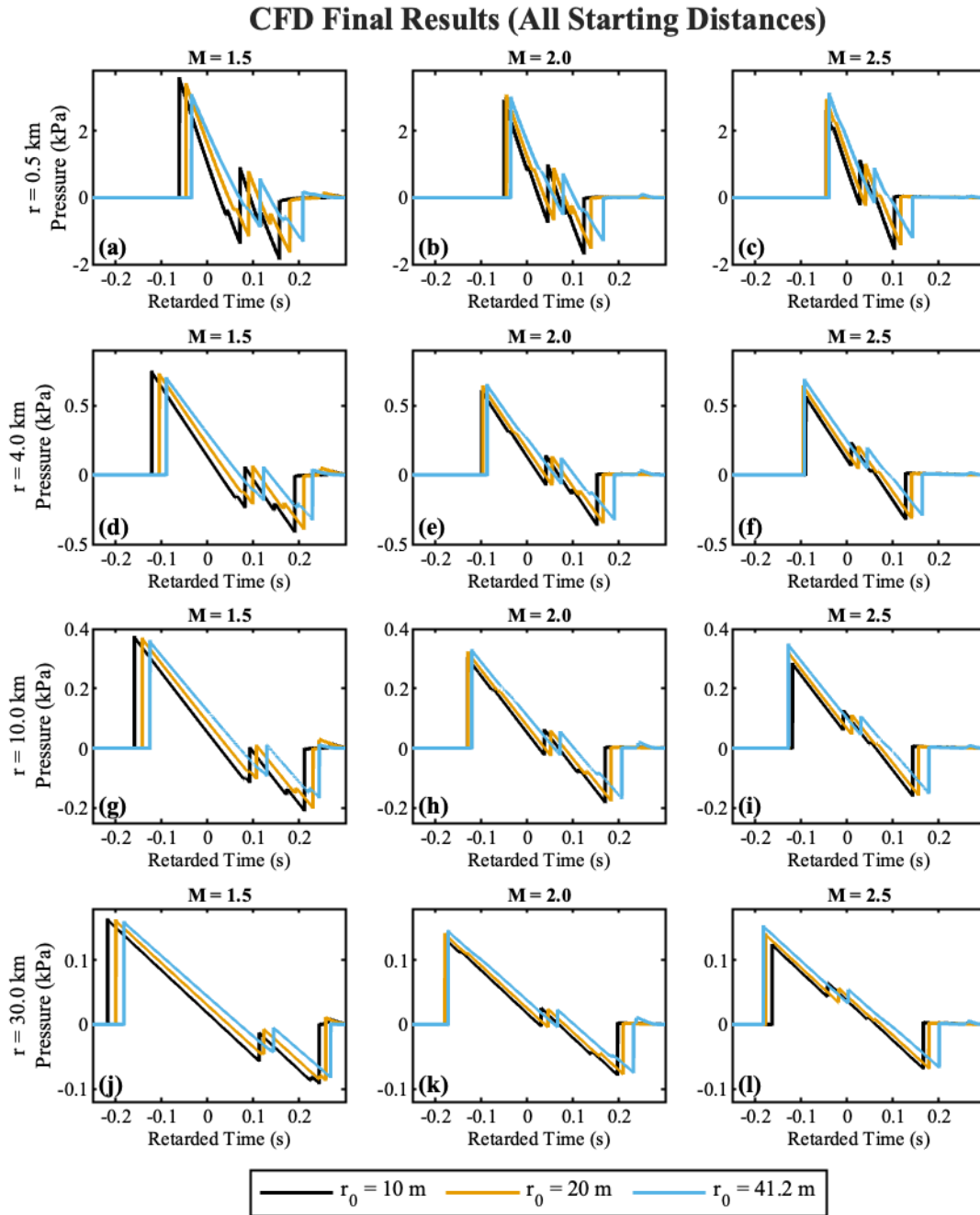


Figure 9.13 Comparing the propagated signatures for the Falcon 9 using three different distances for the near-field pressures. This is to roughly assess the uncertainty in the final results due to the choice of near-field distance.

9.7 Chapter Appendix B: Propagation Code Validation

It is important to validate that the propagation code works properly. The test case shown in this chapter is a comparison with an analytical solution for a planar N-wave (Hamilton and Blackstock, 2024). For an N-wave with an initial overpressure p_0 and initial duration $2T_0$ between the front and tail shocks, the pressure decays as

$$p(r) = \frac{p_0}{\sqrt{1 + \frac{\beta p_0}{\rho_0 c_0^3 T_0} r}}, \quad (9.20)$$

and the location of the front shock changes as

$$T(r) = T_0 \sqrt{1 + \frac{\beta p_0}{\rho_0 c_0^3 T_0} r}. \quad (9.21)$$

Figure 9.14 shows the results of testing the propagation code against the analytic solution for an N-wave with $p_0 = 10$ kPa and $T_0 = 0.2$ s. Subplot (a) shows the input waveform (grey) and the final waveform after propagation with the code (orange) alongside the analytical solution in black. The front shock peak overpressure is considered alongside the analytical result in subplot (b), with the percent error shown in (c). The location of the front shock is shown in subplot (d), with the percent error shown in (e). Overall, the peak pressure error is within 2% and the shock location error is within 1% out to 30 km of plane-wave propagation. Similarly-accurate results were found when using an analytic solution for the peak overpressure of a cylindrically-spreading N-wave (Hamilton and Blackstock, 2024).

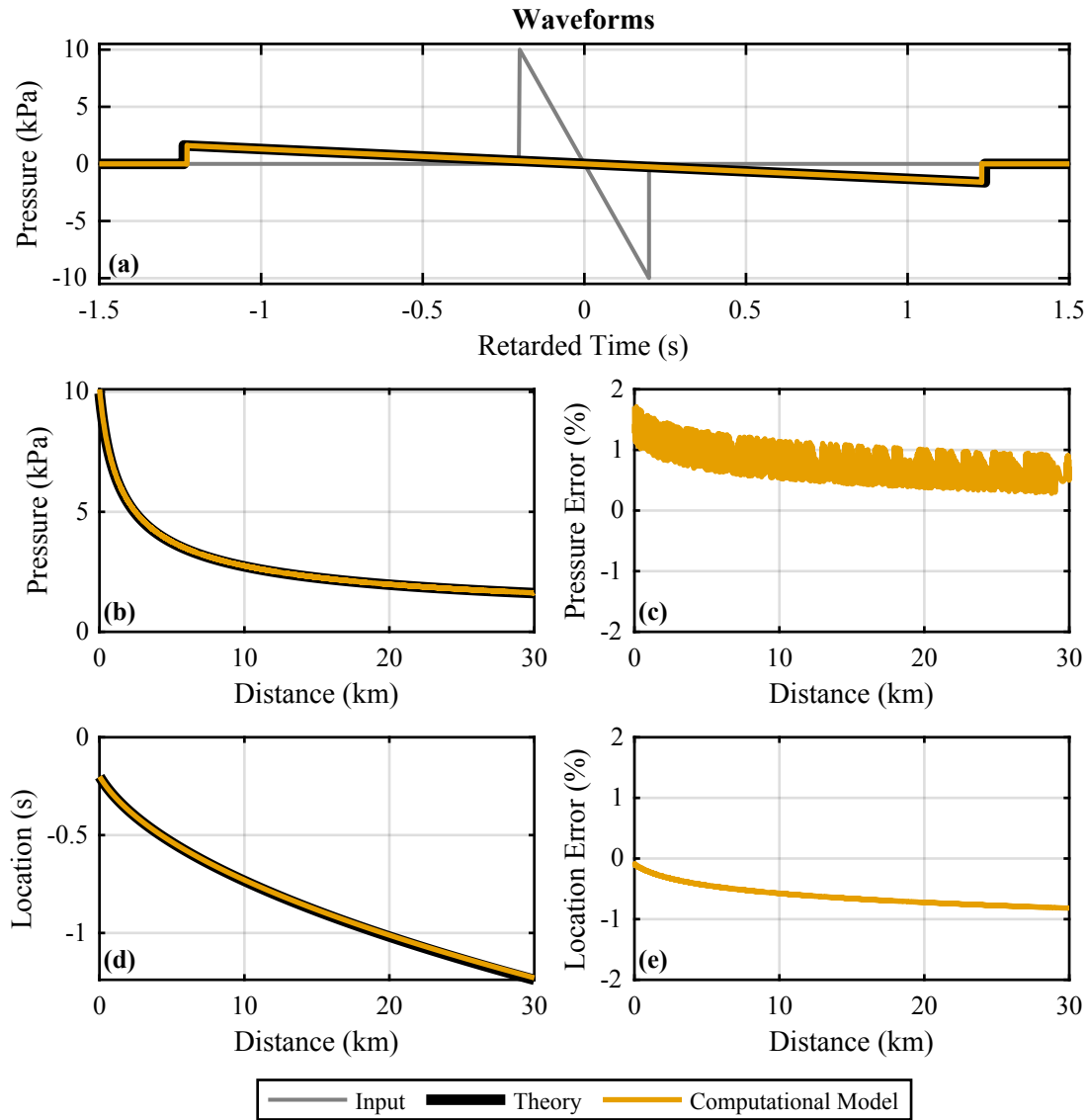


Figure 9.14 Propagation of an N-wave through the Burgers equation code and comparison to analytical results for 30 km of plane-wave propagation. (a) The input and final waveforms. (b) The front shock overpressure compared to analytical results. (c) The percent error for the front shock overpressure. (d) The front shock location compared to analytical results. (e) The percent error for the front shock location.

9.8 Chapter Appendix C: Explaining the Triple Boom with Only a Cylinder

Most of this chapter was derived from Anderson and Gee (2025a). This section is completely unique to this dissertation.

The triple-boom explanation given in this chapter (and in Chapter 8) can be summarized as follows:

1. The first shock comes from the detached bow shock produced by the blunt bottom of the booster.
2. The central shock comes in part from a rarefaction produced as the flow turns around the blunt bottom of the geometry. This rarefaction is of sufficient amplitude to form a shock wave during propagation. The grid fins also produce a shock, and these two shocks merge during propagation to form the second shock in the final waveform. In the end, it is not clear whether the rarefaction from the base or the shock from the grid fins is the dominant feature in producing the central shock, or if they are of comparable importance.
3. The third shock comes from the vehicle termination at the top of the booster. This could be referred to as the “tail” or “wake” shock.

The fact that the grid fins might not be necessary to make the triple sonic boom opens up a potential simpler explanation based solely on a cylindrical geometry. As Shrout *et al.* (1971) demonstrated, a semi-infinite blunt cylinder can produce sonic booms with two shocks because the rarefaction where the flow turns around the geometry can turn into a shock during propagation. If a semi-infinite blunt cylinder produces two shocks, then a finite cylinder of sufficient length could produce the two shocks associated with the vehicle front and then a third shock associated with the vehicle termination. If the cylinder is long enough, then these three shocks will not fully merge during propagation. Because of its simplicity, this possible explanation should be investigated further in future research. A unified theory for all booster shapes that depends primarily on the cylindrical shape would be useful for initial sonic boom modeling efforts for new vehicles.

9.9 Chapter Appendix D: Using the Lighthill F-function

Most of this chapter was derived from Anderson and Gee (2025a). This section is completely unique to this dissertation.

In this chapter, the F-function results tended to produce an N-wave for the Cylinder and a triple sonic boom for the Falcon 9. Meanwhile, the CFD results produced a triple sonic boom for both. While perfect agreement was not expected, as different assumptions underlie both methods, it is possible to improve the F-function analysis.

Specifically, the Whitham (1952) F-function used in the above analyses was not well-suited to the types of geometries considered. The Whitham (1952) F-function assumes a smooth body while the geometries considered here are not smooth. A better approach would be to use the Lighthill (1948) F-function for geometries with slope discontinuities. Although this alternative F-function has been discussed in the literature (Lighthill, 1948; Whitham, 1952; Ritzel and Gottlieb, 1987; Gottlieb and Ritzel, 1988; Jung *et al.*, 2015), it has not been widely adopted.

The Lighthill F-function can be expressed as

$$F_L(x) = \frac{1}{2\pi} \int_0^\infty \left(\frac{2}{\mu R(x)} \right)^{1/2} h \left(\frac{x - \bar{x}}{\mu R(\bar{x})} \right) dS'(\bar{x}), \quad (9.22)$$

where $R(x)$ is the body radius as a function of the distance coordinate x along the body, $\bar{x}$ is a “dummy” variable of integration, $\mu = \sqrt{M_\infty^2 - 1}$, h is a function that takes in the values in the subsequent parentheses, and S' is the first derivative of the cross-sectional area. Similar to the Whitham (1952) F-function, the cross-sectional areas should be taken at the Mach angle. For the same reasons discussed in this chapter, the cross-sectional areas are calculated here at normal angles under the assumption that blunt bodies produce shocks that are not angled at the Mach angle (Carlson and Mack, 1977).

The function h can be expressed as

$$h(z) = \left(\frac{\pi}{2\zeta} \right)^{1/2} \frac{1}{K_1(\zeta)} H(z), \quad (9.23)$$

where z is any numerical input, ζ is Heaviside’s operator of differentiation, K_1 is the modified Bessel function of the second kind, and H is the Heaviside step function. Fortunately, the end user need not calculate $h(z)$ from this equation, as others have done this already and tabulated results and asymptotic solutions (Whitham, 1952; Ritzel and Gottlieb, 1987).

Whitham (1952) provides three example geometries for which F-functions can be calculated. These are shown in Fig. 9.15. Subplot (a) has a semi-infinite geometry beginning with a point and smoothly transitioning to a constant diameter. While Whitham (1952) shows only results with the smooth-body F-function, the Lighthill F-function is shown here to demonstrate that results are similar. Additionally, the Whitham F-function results closely resemble those calculated in his paper. Gottlieb and Ritzel (1988) clarify that the two F-functions are not expected to be exactly equal

except in the limit of a Mach number of unity or an infinitesimally small radius. In subplot (b), a finite smooth body is shown, and again the F-function curves are similar, though not identical. The final geometry, in subplot (c), has multiple slope discontinuities. Recognizing this, Whitham (1952) applied the Lighthill F-function in his paper, and the Lighthill F-function result shown in subplot (c) closely matches his calculation. Note that the Lighthill F-function tends to “anticipate” the slope discontinuities, with the rapid changes in the F-function tending to occur before reaching the actual discontinuity. Throughout, the Lighthill F-function stays finite, as would be expected in a physical system. For completeness in this dissertation, the smooth-body Whitham F-function is also shown in subplot (c). This F-function tends to “blow up” at each slope discontinuity, a result that is not physically accurate in a real system. Similar behavior can be seen in the F-functions calculated previously in this chapter.

Thus, it is preferable to replace the Whitham (1952) F-function calculations in this chapter with calculations using the Lighthill (1948) F-function. This is shown in Fig. 9.16.² Notice that the Lighthill F-function predicts detached shocks ahead of discontinuous slopes. With the Lighthill F-functions now calculated, the near-field pressures can be estimated. These pressures are shown in Fig. 9.17. Notice the peak pressures are a full order of magnitude less than predicted previously by the Whitham F-function, which effectively “blows up” at slope discontinuities.

With near-field pressures defined, the propagation can be carried out exactly as described previously in this chapter. The final propagated results are shown in Fig. 9.18. Overall, both geometries tend toward triple sonic booms. In fact, the Falcon 9 geometry is the only one that results in an N-wave, for Mach 2.5 at 30 km.

These updated methods bring the F-function results into closer alignment with the CFD results, and suggests that the rarefaction produced near the vehicle base may be the dominant contributor to the central shock. The grid fins are still expected to play a role, but it appears to be a smaller role than the rarefaction. It is also useful to note that, at some azimuths, the flow around the booster will pass over the folded landing legs and through the grid fins, but not at all azimuths. At the azimuths where the flow does not pass over the landing legs and through the grid fins, the booster geometry may be more cylinder-like. As the true flow over the booster will have some amount of interplay between all the azimuths, it is likely that the true results lie somewhere between the Cylinder and Falcon 9 results. Full 3D CFD calculations and wind tunnel studies will be required to fully determine which vehicle geometry features are necessary to produce the triple sonic boom.

²Note that, when calculating the nose extension, Eq. (9.3) in this chapter has been replaced with Eq. (4.8) from Ritzel and Gottlieb (1987). This was done because Ritzel and Gottlieb (1987) were deemed to have a clearer expression than the one in Gottlieb and Ritzel (1988), from which Eq. (9.3) was originally obtained. However, the two expressions do not entirely agree, which suggests that more work needs to be done to clarify the appropriate expression.

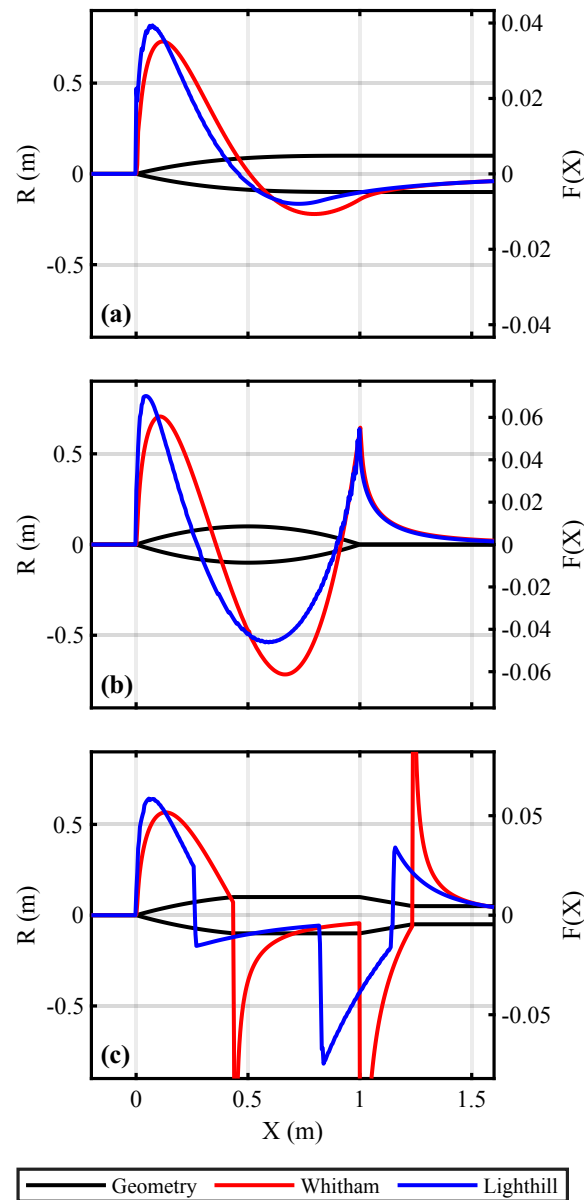


Figure 9.15 Comparisons of F -function calculations across three example geometries given by Whitham (1952). These correspond respectively to graphs C, D, and E in his paper. (a) A smooth semi-infinite pointed geometry. (b) A smooth finite geometry. To reproduce the geometry as plotted by Whitham (1952) in his paper, his equation representing the radius of this geometry must be multiplied by a factor of 4. (c) A 5-10 calibre ogival head bullet, complete with an approximate wake shape.

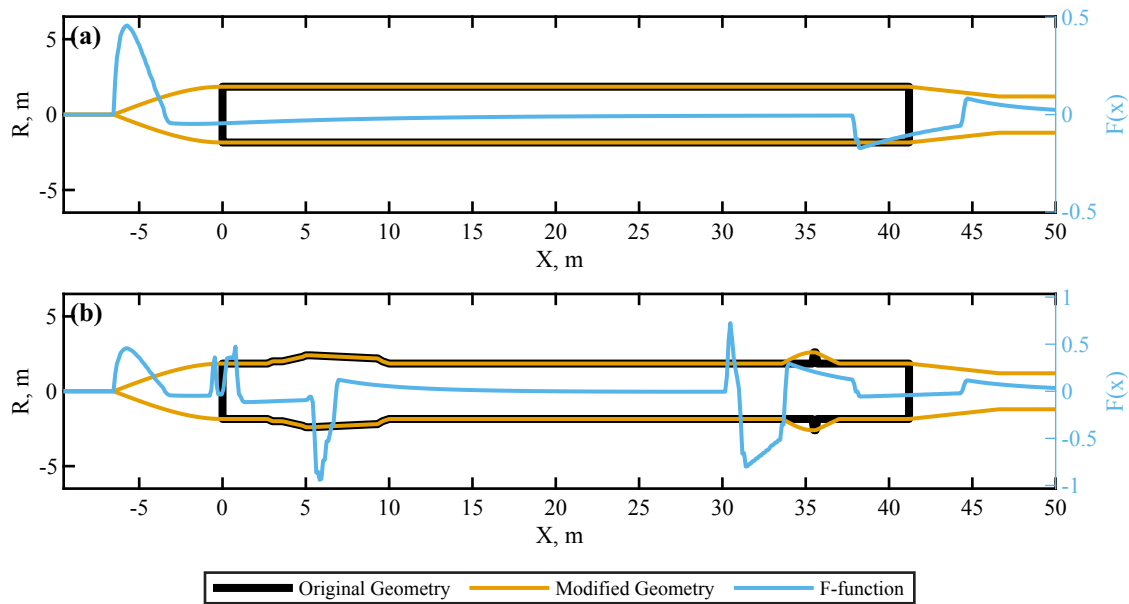


Figure 9.16 Geometries and Lighthill F-functions for the Cylinder (a) and Falcon 9 (b). This figure replaces Fig. 9.3.

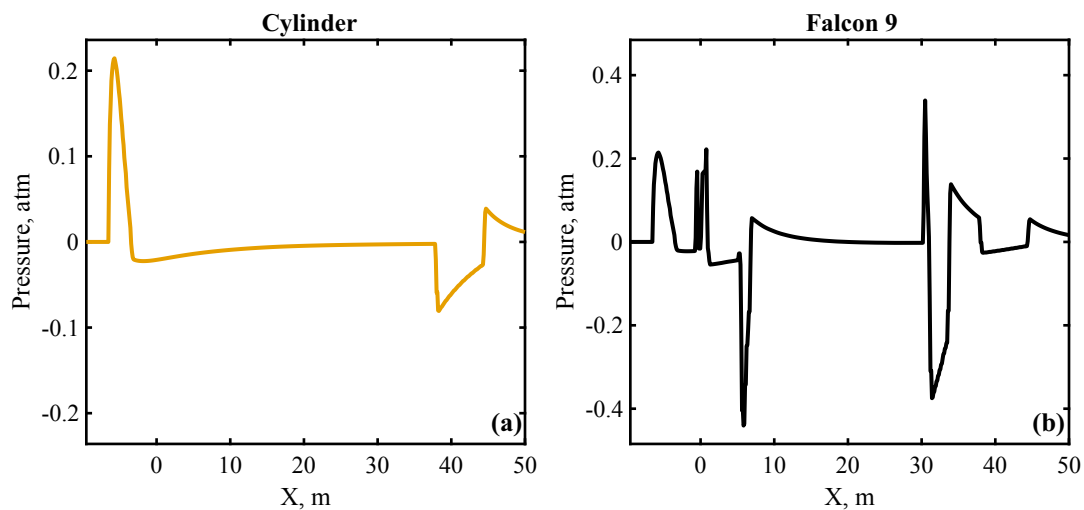


Figure 9.17 Predicted near-field pressures for the Cylinder (a) and Falcon 9 (b). The flow Mach number was 2.0 and the distance r_0 is 41.2 m. This figure replaces Fig. 9.4.

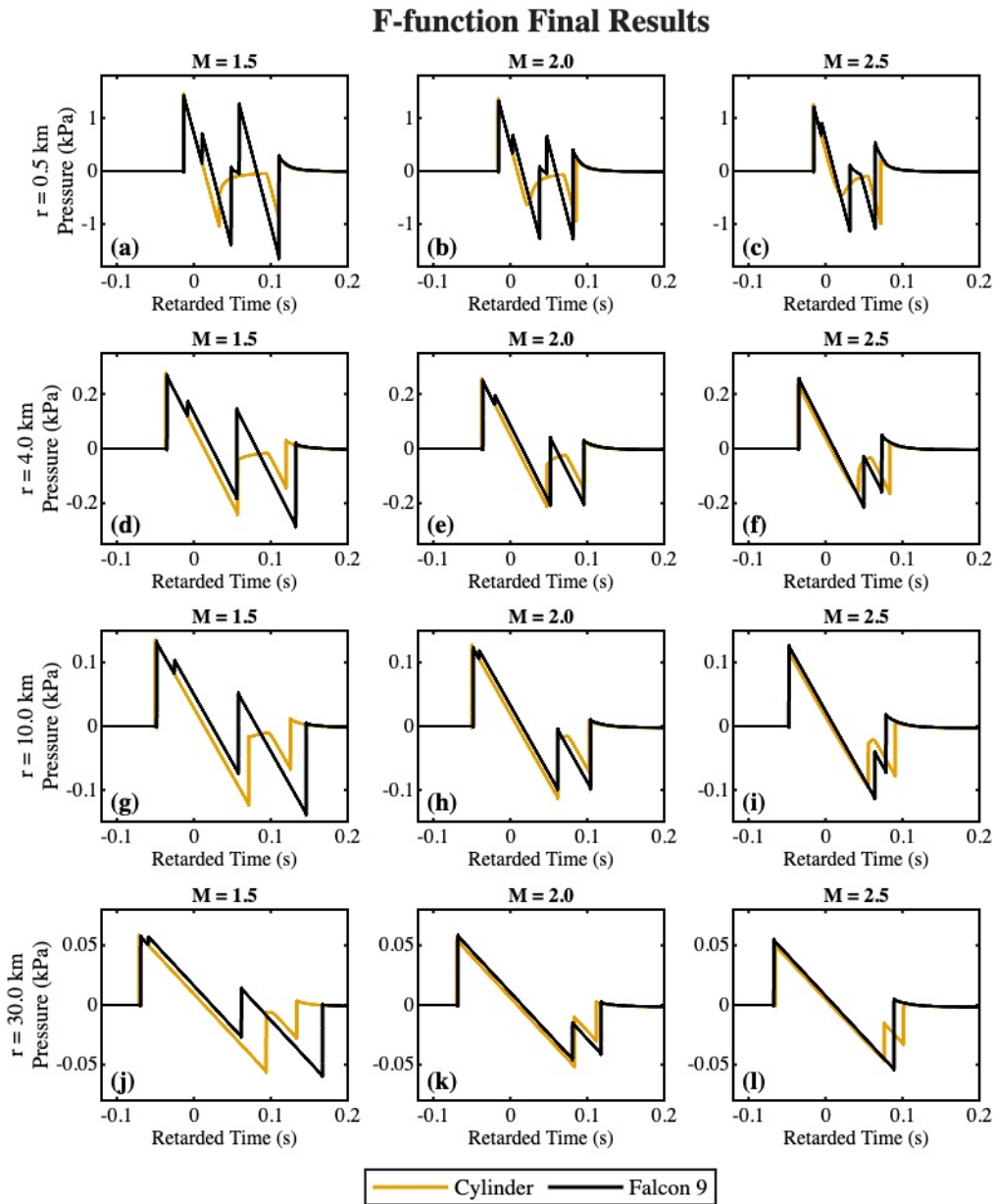


Figure 9.18 Propagated signatures using the Lighthill F-function as input. The Mach number is constant within columns and distance increases between rows. This figure replaces Fig. 9.8.

Part III

Rocket Ascent Sonic Booms

Chapter 10

Modeling Seasonal Weather Effects on Rocket Ascent Sonic Boom Footprints

Abstract

¹When a rocket ascends, accelerates, and pitches over toward orbit, it can generate sonic booms audible on the ground over 100 km from the launch site, as observed with recent launches from Vandenberg Space Force Base (VSFB). The locations where these booms arrive vary seasonally, with some areas experiencing them only at certain times of year. In this chapter, the seasonal variation is explored and modeled using PCBoom 7.5.0, with simulations run using measured and modeled weather profiles from 2020–2025. PCBoom footprints were interpolated to four locations where sonic booms have been reported and measured: Carpinteria, Ojai, Ventura, and Oxnard. The probability of a sonic boom occurring at each location was higher in the winter and lower in the summer (all seasons defined in the northern hemisphere). Changes in the footprint location were linked to seasonal changes in weather. Specifically, the changes in upper-level winds (stratospheric and mesospheric) influenced large changes in the land area that received a sonic boom. Strategic seasonal launch scheduling for missions should be considered to enable launches along all azimuths while minimizing the sonic booms on land.

¹This chapter is being prepared for submission to a peer-reviewed journal. The authors are Mark C. Anderson, Kent L. Gee, and Lucas K. Hall. The interested reader is encouraged to find the published article once available.

10.1 Introduction

As an orbital rocket ascends through the atmosphere at supersonic speeds, it produces a sonic boom. While a strictly vertical trajectory produces an upward-propagating sonic boom, an orbital rocket must pitch over as it ascends so that it reaches the necessary horizontal velocity required for orbit. This pitching over, along with the vehicle's acceleration, produces a sonic boom that intersects the surface below (Glatt *et al.*, 1975a). Such sonic booms were measured in the Atlantic Ocean during Saturn V launches (Hilton *et al.*, 1972; Henderson and Hilton, 1974a,b) and Space Shuttle launches (Garcia *et al.*, 1983b; Stansbery *et al.*, 1983; Stansbery and Stanley, 1984; Stansbery, 1985; Stanley, 2005; Maglieri *et al.*, 2011). Additional measurements have been made of the Titan IV (Stewart, 1993; Francine and Stewart, 1995; Downing and Plotkin, 1996) and the Atlas V (Ortt, 2015). However, almost all previous studies have focused on measuring the sonic boom out at sea, or on islands (Haber, 1981; Wooten and Potter, 1983; Stewart, 1993; Ortt, 2015). Previous studies have also been focused either on the boom centerline or along the boom focus line, and little research has been done outside these regions.

The highest-amplitude portion of the rocket sonic boom footprint is generally the leading edge, where one or more focus booms can occur. Focus booms are the result of multiple sound rays arriving simultaneously and combining to produce a higher overpressure than elsewhere in the footprint (Maglieri *et al.*, 2014). For example, the peak overpressures in the Saturn V focus region were measured as high as 8.9 psf (Henderson and Hilton, 1974b) and 6.8 psf for the Space Shuttle (Maglieri *et al.*, 2011).²

For southeasterly launches from VSF, the sonic boom footprint (including the focus booms) can intercept the areas along the coast of California, like Ventura County (Gee *et al.*, 2026). While sonic booms measured during the summer months of 2024 tended to be mild and of low amplitude, continued measurements indicated a strong seasonal trend in the sonic boom intensity and footprint locations on land (Kellison *et al.*, 2025; Bickmore *et al.*, 2025), with the sonic boom being audible in certain locations only during parts of the year. Conversations with local individuals substantiated the notion that the sonic boom intensity is seasonal. This led to the hypothesis that seasonal weather variation could explain the seasonal variability in the sonic booms on land, which is tested in this chapter.

The purpose of this chapter is to determine whether seasonal weather variation can explain the observed changes in the sonic boom footprints observed in Southern California. The computational model and weather profile data are discussed in Sec. 10.2. The model's outputs are then validated against measured data in Sec. 10.3. Section 10.4 is focused on modeling a single launch trajectory for each day of 2020–2025 and investigating the seasonal trends at four locations. In Sec. 10.5, the upper-level winds are determined to control the footprint location in different seasons. Section 10.6 then proposes a possible solution for sonic boom mitigation on land that would allow for all azimuths to be used for launches, referred to as Strategic Seasonal Launch Scheduling (SSLS). Conclusions are then presented in Sec. 10.7.

²For reference, 1 psf = 47.88 Pascals.

10.2 Methods

10.2.1 PCBoom

NASA's PCBoom 7.5.0 software (Lonzaga *et al.*, 2022, 2025) was used in this study to estimate sonic boom footprint locations and signature overpressures. PCBoom is a software package that combines acoustic ray tracing and nonlinear acoustic propagation to predict footprints, waveform shapes, and metrics for sonic booms. While it has primarily been validated for traditional supersonic aircraft, it has been used for rocket ascent sonic booms in the past (Downing and Plotkin, 1996) and other high-altitude hypersonic vehicle modeling. For example, an earlier version (PCBoom 4) accurately predicted the overpressure and arrival time of a small reentry capsule (Plotkin *et al.*, 2006a).

In this chapter, PCBoom was run in the Carlson Launch mode, which uses the work of Tiegerman (1975) to estimate the sonic boom source function. The methods of Tiegerman (1975) use the drag to estimate sonic booms from hypersonic vehicles and continues to be used in modern spacecraft reentry modeling (Bishop *et al.*, 2025). The time-varying weight and thrust were input in the trajectory data, the plume drag was estimated as 20% of the thrust, and a shape factor curve number (IUN) of 13 was assumed, all following recommendations from the PCBoom User's Manual for a Titan rocket (Lonzaga *et al.*, 2025). Due to software instability when using the enhanced Burgers solver, the lossless solver was used instead under the assumption that the footprint was unaffected by the choice of waveform solver and that the fine waveform details like rise time were not especially important to the present study.

The primary difficulty in relying on PCBoom to accurately predict rocket ascent sonic booms is that there is no well-defined acoustic source model for ascending rockets, whose sonic booms tend to be dominated by the large underexpanded exhaust plume (Hilton *et al.*, 1972; Henderson and Hilton, 1974a; Hicks *et al.*, 1972b; Mendoza, 1975a). Although PCBoom includes a model for a Titan rocket, it uses an equivalent N-wave F-function that attempts to match the true peak overpressure but is not expected to be accurate for the negative phase of the signature. Thus, while the modeled peak overpressures may be close to those measured on the ground, it is not anticipated that PCBoom as used here will accurately model the full ground waveforms. It is possible that future cases could be done with improved source models that better account for the plume effects (see Chapter 11).

Preliminary simulations indicate that the sonic booms reaching the ground in the study area were emitted around 25–65 km in altitude, with the focus booms being emitted near the lower end of this range. Therefore, it is important to obtain corresponding weather profiles over this full range. This is the topic of the next section.

10.2.2 Weather Data

Sample weather profile data are shown in Fig. 10.1. The variables used by PCBoom are the (a) temperature, (b) zonal wind, (c) meridional wind, (d) relative humidity, and (e) pressure. Multiple

sources were used to produce the profiles.³ At low altitudes (0 to ~30 km), weather balloon data were used from the Integrated Global Radiosonde Archive (IGRA) (Durre *et al.*, 2006). These balloons were launched twice daily from VSFB. At medium altitudes (~30 km to ~48 km), the ERA5 reanalysis model was used (Hersbach *et al.*, 2020; CCCS, 2023). While the ERA5 profiles were calculated over Santa Rosa Island (undertrack of the rocket), the ERA5 values at low altitudes agreed well with the radiosonde data from VSFB, demonstrating that the ERA5 data are a reliable proxy for measured profiles. Additionally, this substantiates the assumption here that, within the study region, the weather data can be assumed range independent. At high altitudes above the range of the ERA5 simulations (~48 km to 70 km), a range reference atmosphere for each month (Boire *et al.*, 1983, see the Chapter Appendix) was used for the wind components while a 1976 standard atmosphere was used for the temperature and pressure (NOAA *et al.*, 1976). To reduce steep gradients occurring when the top point of the ERA5 simulation does not match the high-altitude reference or standard atmosphere, the high-altitude atmospheric data begin at 56 km and the values between ~48 km and 56 km are linearly interpolated. While it is possible to investigate many different models and methods for constructing the full weather profiles, it is worth noting that Anderson *et al.* (2025) and Lympny *et al.* (2025) presented independent studies of weather effects on rocket ascent sonic boom footprints where each used different weather data sources. Anderson *et al.* (2025) used only the IGRA weather balloon data while Lympny *et al.* (2025) used the NASA Horizontal Wind Model 2014 (Drob *et al.*, 2015). The trends and conclusions agreed with each other and with those found in this chapter. While different weather models should be investigated in the future, the conclusions in this chapter are not expected to be especially sensitive to model choice. Additionally, the trends observed in this chapter were independent of whether the data at 0000 UTC or 1200 UTC were used. Therefore, except where appropriate in Sec. 10.3, only the 1200 UTC data are shown in the remainder of this chapter.

10.3 Validation Against Measured Data

To determine whether the PCBoom results can be relied on for this use case, it is necessary to first demonstrate the degree to which the PCBoom simulations agree with measured data. Contributing to this validation, acoustic measurements were performed beginning in June 2024 (Kellison *et al.*, 2025; Gee *et al.*, 2026) and continued through 2025 (Bickmore *et al.*, 2025). Though full results have not yet been published, a subset of the measured data is shown in Fig. 10.2 for comparison with simulations. The simulations were all performed using a single Starlink Group 9 first-stage trajectory (terminating at engine cutoff) provided by VSFB, which is also similar to the Starlink Group 11 trajectory. Therefore, the only differences between the simulations are the weather data. The launches considered are the Starlink 9-3 (July 12, 2024), Starlink 9-4 (July 28, 2024), Starlink 11-2 (December 14, 2024), and Starlink 11-11 (April 8, 2025) missions. As expected based on previous measurements (Hilton *et al.*, 1972; Henderson and Hilton, 1974a,b), the pressures at

³The exception to these details is the relative humidity, which was not available from the IGRA or monthly reference atmospheres, and so comes entirely from the ERA5 simulations. At points higher than the ERA5 simulation data, PCBoom assumes the highest-defined value persists to all higher altitudes (Lonzaga *et al.*, 2022).

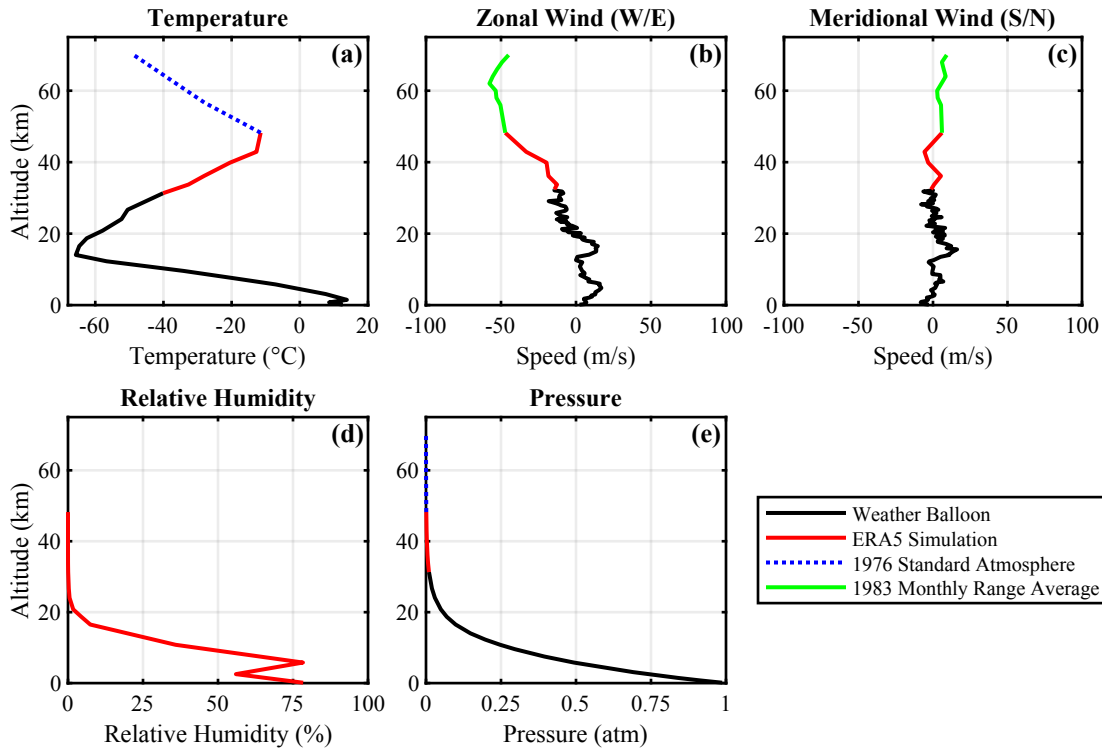


Figure 10.1 Example weather profiles (19 June 2023). The five variables considered in the simulations are the (a) temperature, (b) zonal wind (west-blowing is negative, east-blowing is positive), (c) meridional wind (south-blowing is negative, north-blowing is positive), (d) relative humidity, and (e) pressure. Values are colored according to data source.

the start of the footprint (northwest) are highest and the pressures tend to decrease with distance from this high-pressure “focus” region, though the pressure decreases through the footprint are not monotonic when atmospheric effects are taken into account as shown in Fig. 10.2. It is worth noting that while the analyses in this chapter are limited to the sonic boom produced during the first stage phase of flight, a sonic boom is still expected to be produced by the second stage. This second stage sonic boom would continue the footprint toward the southeast, gradually decreasing in amplitude as the rocket ascends to higher altitudes.

The agreement between the PCBoom simulations and the measurements validates the use of PCBoom for the remainder of this chapter. By this, it is meant that the footprint shapes are similar between PCBoom and measurements, and a rigorous comparison of overpressure amplitudes is not directly considered here. For Starlink 9-3, few booms were measured on land, and those that were measured had low overpressures, typically below 0.1 psf. This was mirrored by the simulations, which predicted that the footprint terminated offshore. In reality, a region outside the predicted sonic boom footprint is expected to receive low-amplitude acoustic waves (Maglieri *et al.*, 2014), explaining why such low-amplitude signatures could still be recorded outside the primary carpet.

The Starlink 9-4 launch, which occurred only 16 days after the 9-3 launch, created sonic booms over more land area, and this is reflected in the simulations. The Starlink 11-2 launch produced a substantially different footprint on land. Sonic booms were measured as far north as Ojai and as far west as Santa Barbara, a change that is predicted by the simulation. Lastly, the Starlink 11-11 simulation indicates that the focus should again pass through the northern portion of the study area, a result that is also visible in the measurements. Thus, it is concluded that PCBoom 7.5.0, when coupled with proper weather data, is capable of approximating the trends in measured footprint locations.

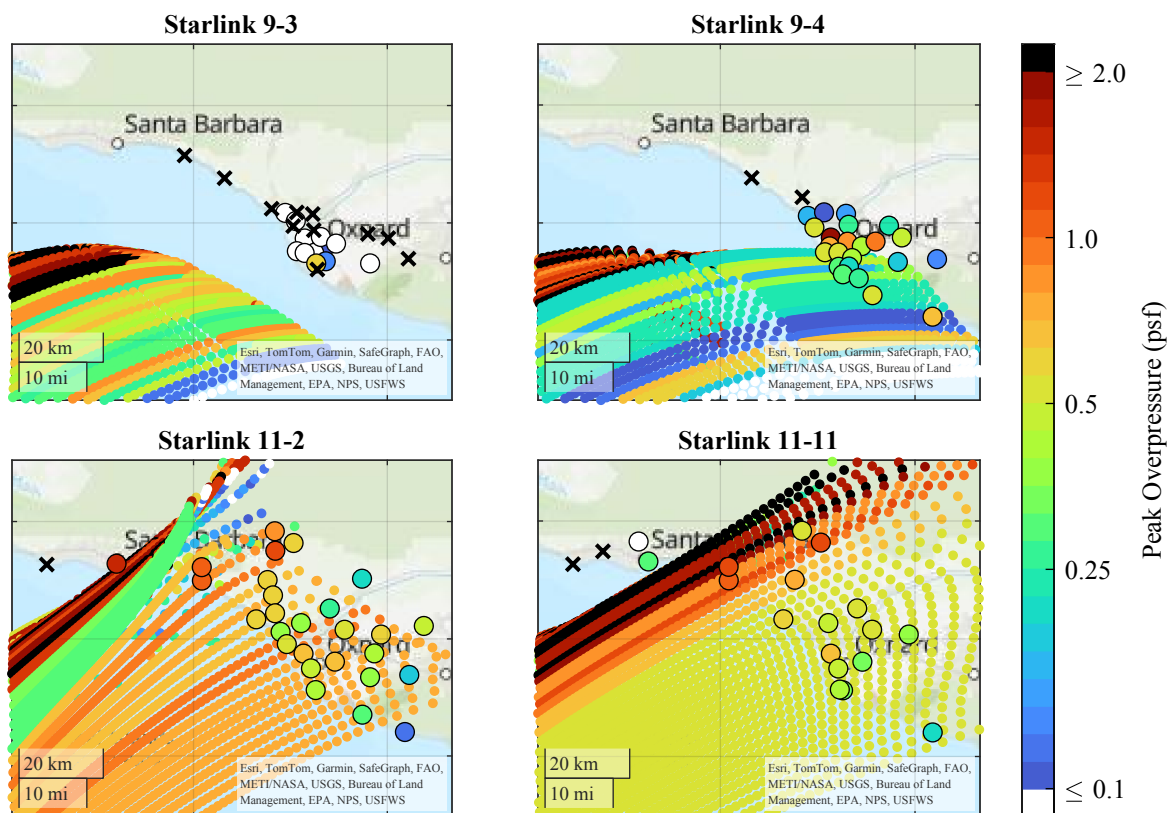


Figure 10.2 Demonstration that PCBoom simulations can approximate the overall footprint behavior for four launches including the Starlink 9-3 (July 12, 2024), Starlink 9-4 (July 28, 2024), Starlink 11-2 (December 14, 2024), and Starlink 11-11 (April 8, 2025) missions. The only differences between the simulations are the weather profiles, where the closest weather profile in time for each launch (either before or after) was used for each simulation. PCBoom simulation results are indicated by small circles, and the measured results are indicated by the larger circles with black borders. Locations where measurements were performed but no boom was observed are indicated by a black “x” and demonstrate that the leading edge of each footprint was captured by the measurements.

10.4 Footprint Modeling Between 2020–2025

To assess the effects of seasonal weather patterns on the sonic boom footprint, the same Starlink Group 9 trajectory was used to simulate flights with weather profiles taken from nearly every day of 2020–2025, only missing days where the weather balloon data could not be obtained. The trajectory contains only the first-stage portion of flight and terminates at first-stage engine cutoff on ascent. The peak overpressures were interpolated to four locations within the study area: Carpinteria, Ojai, Ventura, and Oxnard, shown in Fig. 10.3. The peak overpressure results are shown in Fig. 10.4 as a function of day. The reader is cautioned that, although there is a correlation between sonic boom peak overpressure and sonic boom perception (Naka, 2013), there are other metrics that are much better correlated (Naka, 2013; Loubeau *et al.*, 2015). Other than overpressure, a key factor in determining sonic boom perception is the shock rise time (Loubeau and Page, 2018; Shepherd and Sullivan, 1991). Thus, the overpressure results shown in this chapter should not be taken to directly indicate sonic boom perception, and future analyses need to be performed to rigorously determine the perception of launch-ascent sonic booms. Anecdotally, pressures around 1 psf tend to be clearly audible, and higher pressures even more so. Lower pressures are also generally audible but can become decreasingly audible as the pressure drops. The three northernmost locations (Carpinteria, Ojai, and Ventura), show strong seasonality, tending to have almost no booms in the summer months (defined as May to September) while having some of the highest-amplitude booms in the winter months (defined as October to April). This result can be explained because these locations are on the northern edge of the footprint and so tend to receive no boom (outside the footprint) or are near the focus boom (barely inside the footprint). The southernmost location (Oxnard) also shows seasonality in peak overpressure, though it is not quite as prominent as at the northern locations.

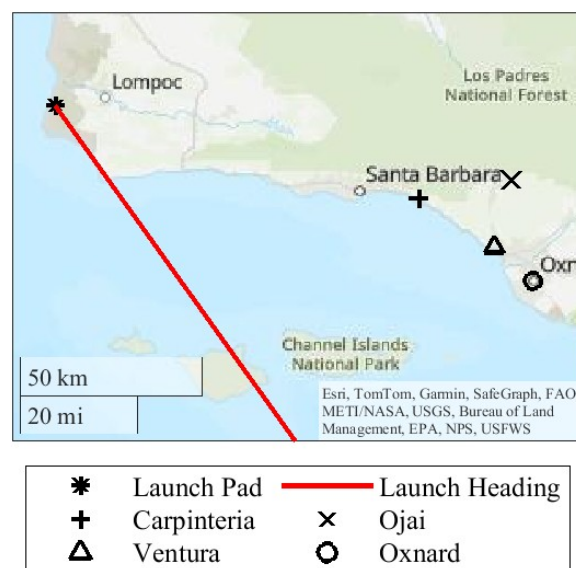


Figure 10.3 The selected locations for further analysis along with the launch location and a 144° trajectory ground track representative of the trajectory used in this study.

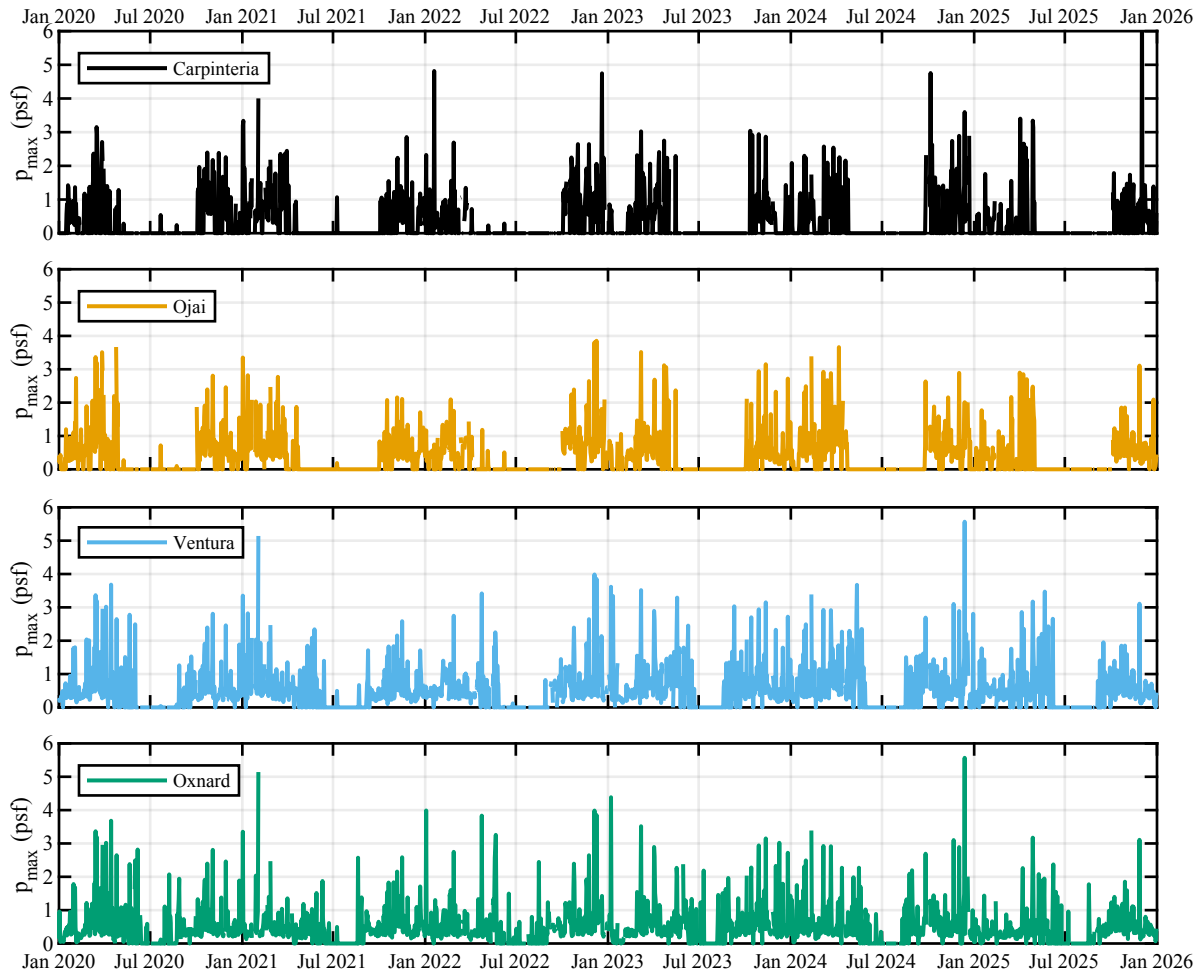


Figure 10.4 Simulated overpressure predictions at each of the four locations. PCBoom footprints from each day were interpolated to each location. The only value exceeding the axis limits is on Dec. 12, 2025, for Carpinteria, with an overpressure of 7.2 psf. While all the overpressures higher than 4 psf were inspected and found to be valid interpolations, only one (Carpinteria, Jan. 19, 2022) was found to result from a convex footprint shape that may have exaggerated the overpressure.

To simplify the visualization of seasonal trends, the data in Fig. 10.4 were used to produce Fig. 10.5. To produce these results, the simulations in Fig. 10.4 were aggregated according to month. Subplot (a) shows the percentage of days in each month where PCBoom (with the corresponding weather conditions) predicts that a boom should occur at each location. Although Ventura and Oxnard consistently have higher overall boom percentages, all four locations had lower percentages (dropping below 20%) at some time during the summer months and higher percentages (rising above 70%) at some time during the winter months. However, because subplot (a) only considers whether a boom of any amplitude occurred at each location, it is useful to consider also the median

boom overpressures for each month, shown in subplot (b). Days where booms are not predicted to occur at a given location have overpressures of zero. The same trends are again visible, with median overpressures dropping to 0 psf in the summer months and rising above 0.5 psf at some point in the winter months. Lastly, while subplot (b) shows the median values including days without booms predicted at each location, subplot (c) shows the median overpressures including only those days where booms are predicted to occur for each given location. In this result, seasonal variation in overpressure is location-dependent, with less variation at the southernmost location (Oxnard, 0.3–0.7 psf) and more at the northernmost location (Carpinteria, 0.2–1.6 psf).

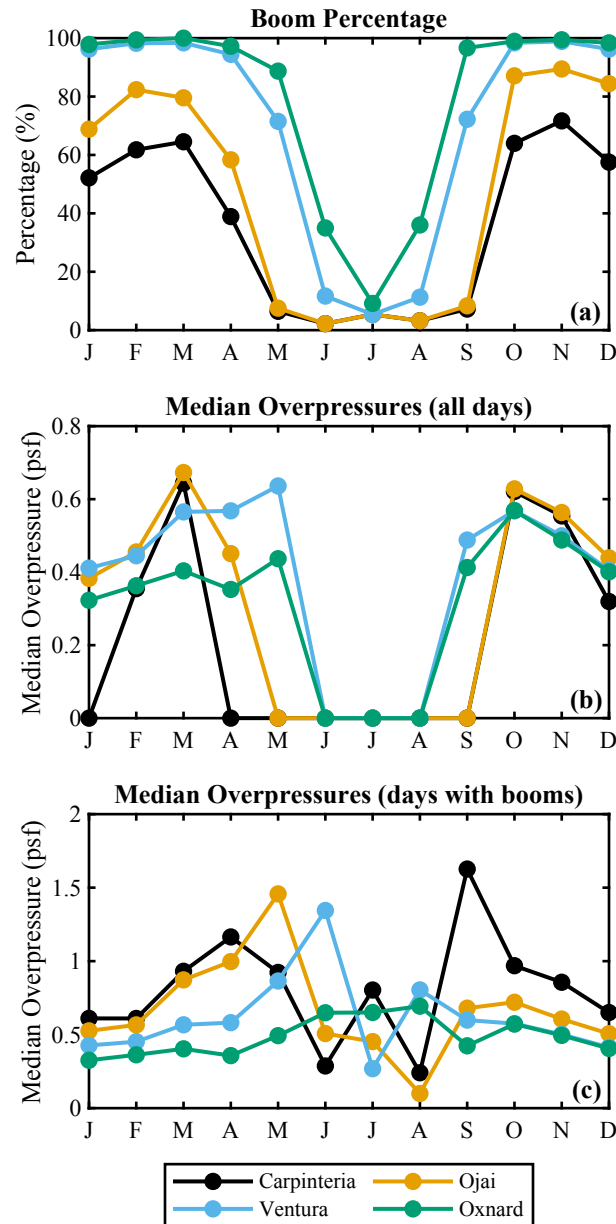


Figure 10.5 The seasonal variation in sonic booms at each location of interest. (a) The percentage of days in each month where the weather conditions cause a sonic boom to reach each location. (b) The median overpressures for each month, with no-boom days included as 0 psf. (c) The median overpressures for each month, but with no-boom days discarded.

10.5 Assessing Meteorological Factors

There are only five meteorological inputs to PCBoom: temperature, wind (zonal and meridional components), pressure, and relative humidity. Of these, only the temperature and wind (which can both strongly affect the local sound speed) are anticipated to play a dominant role in the ray tracing that determines the final footprint location. These variables are considered in Fig. 10.6, showing the median profiles across the entire study period for the seven winter (October–April) and the five summer (May–September) months. These time periods were chosen based on the trends observed in Fig. 10.5. While the median temperature profiles appear similar for the two seasons, the upper-level (stratospheric and mesospheric) wind directions (>15 km) come from different directions and the upper-level wind speed profiles gradually diverge. In the winter months, these winds mostly travel from the west towards land and, in the summer months, the winds travel from the east towards the ocean. Because the largest relative differences in weather profiles occur for the wind direction, where there is almost a complete reversal of direction above 40 km, the following analysis will focus on how the upper-level wind direction affects the footprints.

To study the possible effects of upper-level wind direction on the sonic boom footprint, PCBoom simulations were performed using eight different wind direction profiles, shown in Fig. 10.7(a). This study isolates the effects of upper-level wind direction and determines whether the upper-level wind differences in the winter (westerly/east-blowing winds) and summer (easterly/west-blowing winds) can account for the observed seasonal trends in footprint location. Below 15 km, the wind direction profiles all converge to the median wind direction across the entire multiyear simulation period and above 15 km they separate to eight different directions. For all simulations, the median wind speed profile across the full multiyear simulation period was used and is shown in Fig. 10.7(b). Similarly, the temperature, pressure, and relative humidity profiles used here are the median profiles across the full multiyear simulation. Because the real-world upper-level winds in this region tend to have a strong zonal component (see the Chapter Appendix), the simulations with easterly or westerly wind components (NE, E, SE, SW, W, NW) are expected to be more physical, while the purely northerly (N) and southerly (S) wind directions are included for completeness.

The simulation results are shown in Fig. 10.8. Each subplot corresponds to the upper-level wind coming from a particular direction and an arrow is included in each subplot to further clarify the wind vector. Locations corresponding to those in Figs. 10.3–10.5 are indicated. When the upper-level winds originate from the north, northeast, east, or southeast, there is an eastern lateral cutoff to the sonic boom footprint on land within the axis limits. However, when the upper-level winds originate from any of the other directions (south, southwest, west, or northwest), the eastern lateral cutoff is much farther inland. In fact, for the southwesterly and westerly wind cases, the footprint reaches as far (or farther) inland as Lancaster, CA. The westerly winds also tend to produce a footprint that places Carpinteria and Ojai on the northern edge of the footprint, making it clear that these locations are at a higher probability of experiencing a focus boom when the upper-level winds blow from any of the westerly directions. These results validate the claim that changes in upper-level wind direction can explain the seasonal variation observed in measurements.

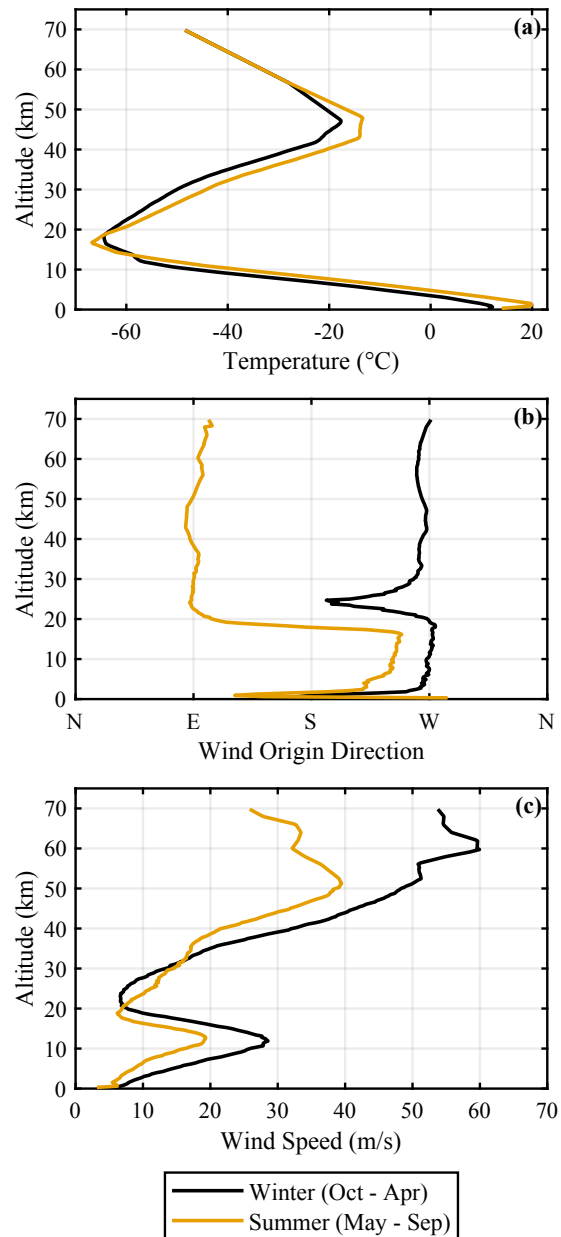


Figure 10.6 The meteorological factors expected to predominantly shape the footprint. Median profiles are shown for two time periods: winter (October–April) and summer (May–September). The variables considered are the (a) temperature, (b) wind direction (defined as the direction from which the wind originates), and (c) wind speed.

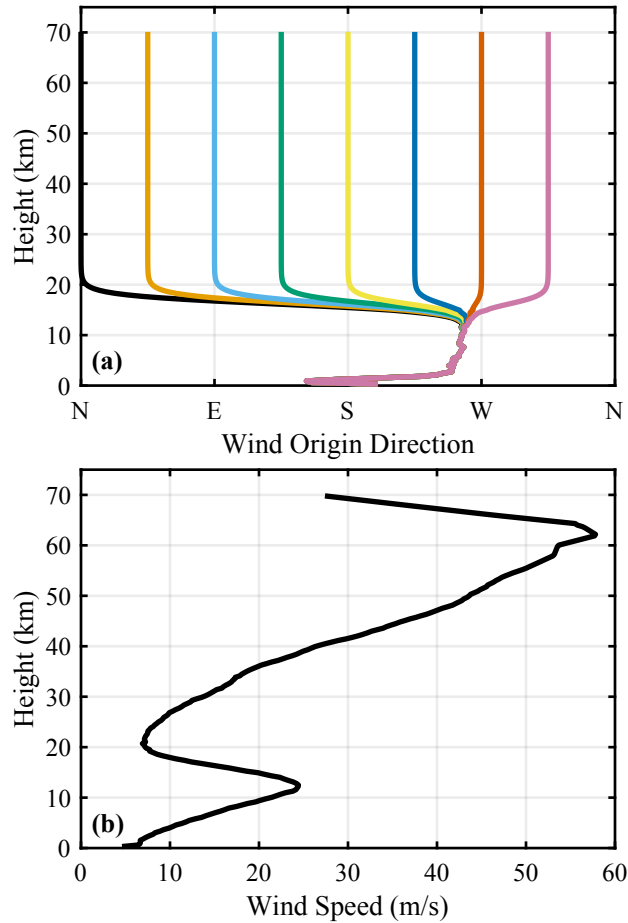


Figure 10.7 Wind profiles used in the PCBoom wind effects analysis. (a) The wind direction as a function of height. Values above 15 km are coerced to particular directions while values at lower altitudes correspond to the median taken over the full range of dates in the multiyear simulations. (b) The median wind speed as a function of height over the full range of dates in the multiyear simulations.

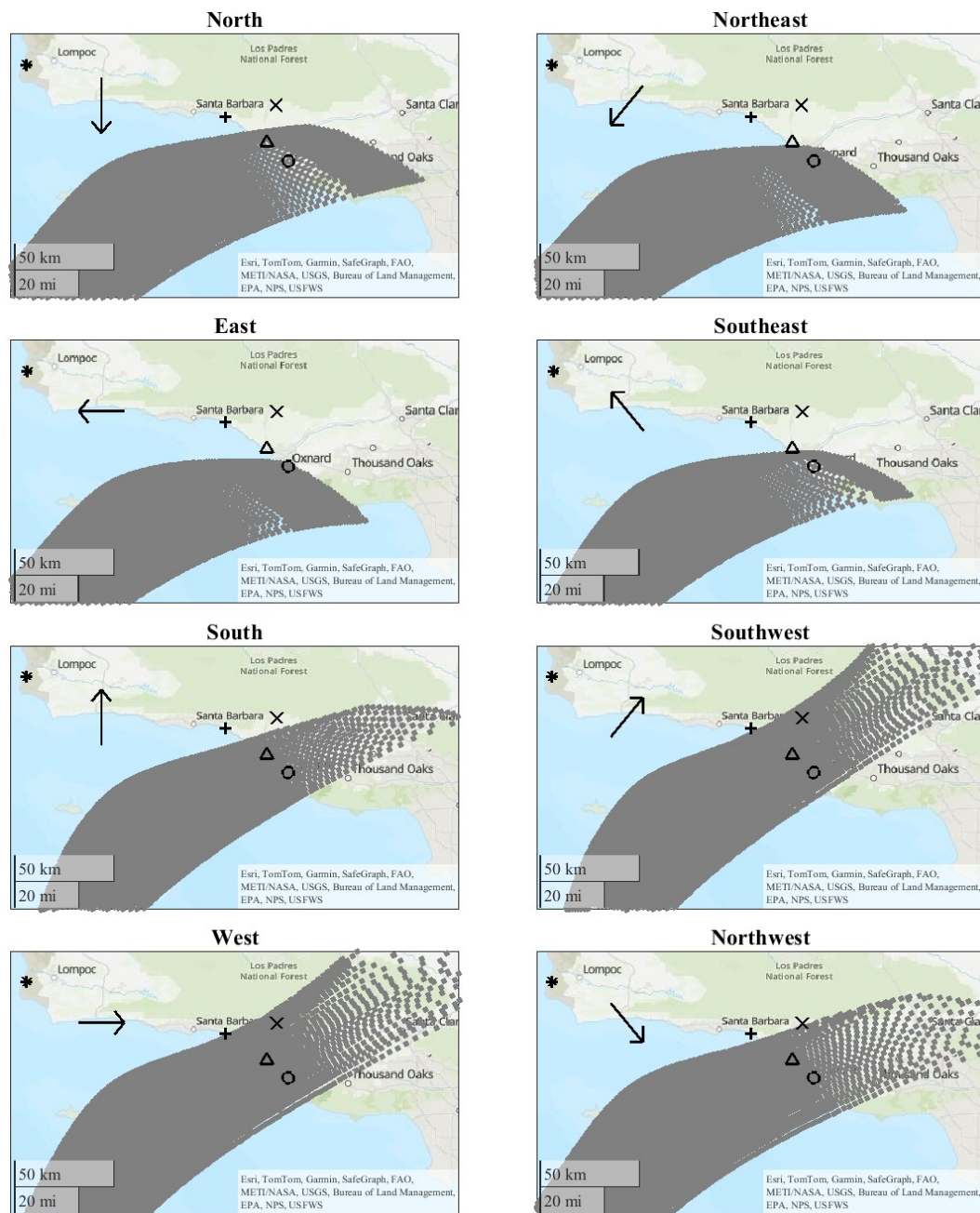


Figure 10.8 The effects of upper-level (>15 km) wind direction on the sonic boom footprints. Locations of interest include Carpinteria (+), Ojai (x), Rincon Point (+), Ventura (triangle), Oxnard (circle), and the launch site (*). Upper-level wind direction vectors are indicated on each subplot by an arrow. The titles indicate from which direction the upper-level winds originate. To keep the emphasis on footprint shapes, a uniform gray color is used for all points.

10.6 Strategic Seasonal Launch Scheduling

With the connection made between seasonal weather and sonic booms on land, it is possible to discuss a potential mitigation solution, referred to here as “Strategic Seasonal Launch Scheduling” (SSLS). The goal is to enable launch providers to launch all their missions while simultaneously reducing the sonic boom footprints on land. If launch schedules can be flexible, then SSLS is a promising path forward.

SSLS at VSFB operates on the principle that coastal trajectories in winter months (October–April) tend to produce high-amplitude sonic booms over relatively large land areas while the same trajectories in summer months (May–September) produce sonic booms that cover less land area and typically have lower amplitudes on land. For example, the probability of receiving a sonic boom in Ojai for a given launch along this 144° trajectory on a random day in the summer months is modeled to be less than 10%, while the probability for a launch in the winter months is modeled to be over 60% and even as high as 90% depending on the month (see Fig. 10.5). Thus, it is proposed that coastal trajectories be strategically launched in the summer months while trajectories farther from the coast be launched in the winter months. This could enable launch providers to launch all their planned missions throughout the year while reducing the sonic boom footprints on land.

A full study of different trajectories throughout different seasons will be required before recommendations for implementing SSLS can be concretely given, and such a study is beyond the scope of this chapter. However, this chapter provides the initial evidence that strategically scheduling the launches throughout the year has the potential to reduce the sonic boom footprints on land.

10.7 Conclusion

Rockets launching along the California coast have been producing audible sonic booms on land over 100 km away from the launch site. Evidence from measurements and discussions with local community members suggested that these sonic booms are not observed for every launch and that the likelihood of experiencing one changes throughout the year. This led to the hypothesis that recurring seasonal weather patterns can dramatically affect the sonic boom footprint location.

The goal of this chapter was to test this hypothesis and determine dominant meteorological variables. All simulations were performed using a 144° SpaceX Falcon 9 first-stage ascent trajectory in PCBoom 7.5.0, which was validated against measurements in this chapter. Simulations were run using measured and modeled weather profiles from 2020–2025. Each stratified atmosphere was used to produce ground footprints. The footprints were then interpolated to four locations in the study area, within the communities of Carpinteria, Ojai, Ventura, and Oxnard.

Strong seasonality was observed at the locations in the study. For all locations, there is a boom “season” lasting primarily from October–April (seven months), where launch trajectories along this 144° heading are substantially more likely to produce higher-amplitude sonic booms over a relatively large land area. During the remaining months, from May–September (five months), the launches along this heading produce far fewer sonic booms on land, with the exact amount being location-specific (Fig. 10.5), and the overpressures on land tend to be lower. It was determined that

the seasonal changes in upper-level winds play a strong role in driving these large seasonal changes in sonic booms on land.

Using these results, it is proposed that strategic seasonal launch scheduling (SSLS) be investigated as a means of reducing the sonic boom footprints on land while still enabling launch providers to launch all their missions each year. This could be implemented by launching coastal trajectories primarily in the summer months (May–September) when they are less likely to produce high-amplitude sonic booms over large land areas. Subsequently, the trajectories that are farther from the coast can be primarily launched during the winter months (October–April) so that the sonic boom footprint on land is reduced. Further studies of different trajectories through different seasons will need to be performed before concrete recommendations can be given, but this chapter provides initial insight that this strategy could work.

Acknowledgments

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10.8 Chapter Appendix: Range Reference Atmospheres

The monthly range-reference atmospheres were obtained from a 1983 report about Vandenberg Air Force (now Space Force) Base entitled “Range Reference Atmosphere 0–70 km Altitude” (Boire *et al.*, 1983). The monthly wind profiles were extracted for use in this chapter, while the pressure and temperatures were not sufficiently legible and the relative humidity was not directly available. The wind components are shown in Fig. 10.9. Although only the top portion (56–70 km) of these wind profiles were used in the analyses in this chapter, these profiles are included here to illustrate the seasonal changes in the winds that are discussed throughout this chapter. Although not shown, the mean monthly wind profiles created for this chapter agree well with the profiles in Fig. 10.9 at all altitudes.

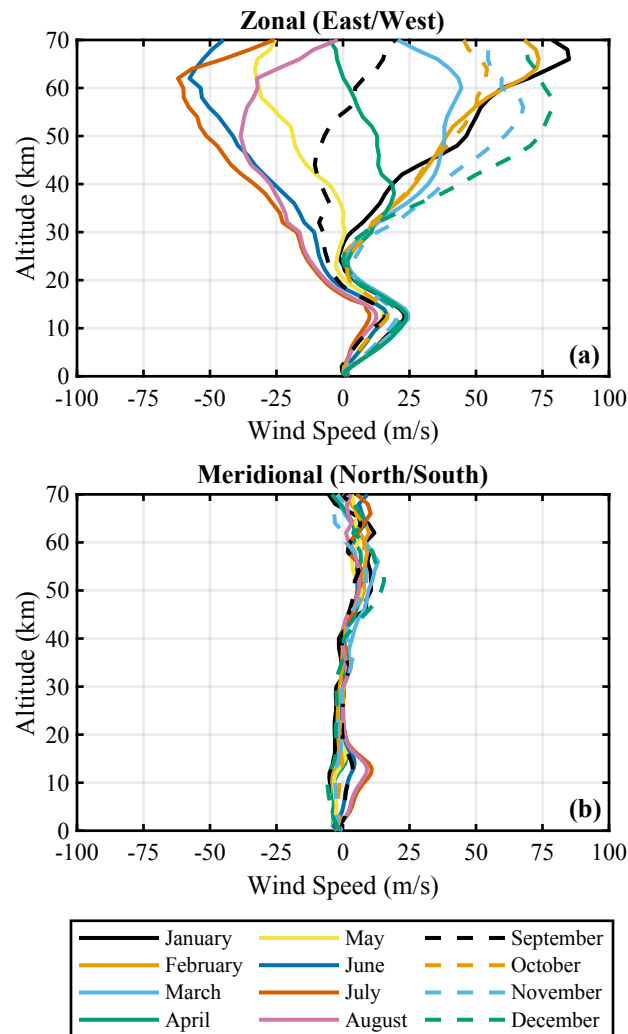


Figure 10.9 The monthly range reference atmospheres for the region studied in this chapter. Data extracted from Boire *et al.* (1983). In (a), a positive number indicates a westerly (eastward blowing) wind component and vice versa. In (b), a positive number indicates a southerly (northward blowing) wind component and vice versa.

Chapter 11

Modeling Rocket Ascent Sonic Boom Waveforms, Including Plume Effects

Abstract

¹When a rocket flies through the atmosphere at supersonic speeds, it produces a sonic boom. Because orbital rockets need to pitch over to reach orbit, this sonic boom reaches the ground downrange. During the NASA Apollo and Space Shuttle missions, such sonic booms were found to have a different characteristic shape from the traditional N-waves expected from most other aircraft. Namely, these launch-ascent sonic booms consisted of a (1) front shock, (2) rarefaction, (3) gradual return to ambient, and (4) duration of several seconds. The overall shape appeared much more like a blast wave with a duration a full order of magnitude longer than traditional aircraft sonic booms. In this chapter, all four characteristics are successfully modeled when using a simplified vehicle-plus-plume geometry, estimating near-field pressures via the Lighthill F-function, and propagating to the ground using the Burgers equation. It is also demonstrated that, using the Hilbert transform, realistic waveform shapes can be modeled near the focus. This is the first time that full rocket launch-ascent sonic boom waveforms have been modeled, leading toward improved near-field estimates for sonic boom propagation models. Such improved models will be necessary as the global launch cadence continues to increase, and more areas are exposed to launch-ascent sonic booms.

¹This chapter is being prepared for submission to a peer-reviewed journal. The authors are Mark C. Anderson and Kent L. Gee. The interested reader is encouraged to find the published article once available.

11.1 Introduction

As an orbital rocket ascends, accelerates, and pitches over, it produces a sonic boom downrange that reaches the Earth's surface. Such sonic booms are always produced during an orbital launch (Glatt *et al.*, 1975a), though they typically occur over the ocean. The first detailed measurements of launch-ascent sonic booms were made during the NASA Apollo program (Hilton *et al.*, 1972; Henderson and Hilton, 1974a,b; Holloway *et al.*, 1973; Hilton and Henderson, 1974). Measurements were made by placing microphones on ships near the anticipated vehicle ground track. Such measurements were then repeated during the Space Shuttle program (Garcia *et al.*, 1983a; Stansbery and Stanley, 1984; Stansbery *et al.*, 1983; Stansbery, 1985; Maglieri *et al.*, 2011). However, once initial models for peak overpressure and positive-phase impulse were validated, little additional research on launch-ascent sonic booms was published over the next several decades. Exceptions include some conference presentations (Stewart, 1993; Francine and Stewart, 1995; Downing and Plotkin, 1996; Stanley, 2005) and additional works typically focused on environmental applications (Ortt, 2015; NMFS and NOAA, 2013).

In recent years, launch-ascent sonic booms have become relevant again. This stems in part from the fact that launch trajectories from Vandenberg Space Force Base (VSFB) have moved closer to the southern California coast, resulting in sonic booms along the coastal land areas more frequently (Green-Lanchoney, 2025, 2026; Gee *et al.*, 2026). This has prompted new studies into launch-ascent sonic boom formation and propagation. Using modern recording hardware and computational capabilities, new physical insights into these unique sonic booms are being generated, including the effects of atmospheric variation on launch-ascent sonic boom footprints (Anderson *et al.*, 2025; Lympny *et al.*, 2025).

One of the remaining questions about launch-ascent sonic booms can be summarized as follows: “Why are launch-ascent sonic booms not N-waves?” Typically, when an aircraft produces a sonic boom, the many near-field shocks coalesce into single bow and tail shocks connected by a linear ramp, giving rise to the term “N-wave” based on the waveform shape (Maglieri *et al.*, 2014). Instead, the four characteristic properties for rocket launch-ascent sonic booms as measured on the Earth's surface (see Fig. 11.1) are a (1) front shock, (2) rarefaction, (3) gradual return to ambient, and (4) duration of several seconds. While traditional aircraft sonic booms tend to have a distinct N-wave shape lasting at most a few tenths of a second (Maglieri *et al.*, 2014), these ascent boom waveforms look more like long blast waves with durations a full order of magnitude greater than traditional aircraft. They are also dissimilar to reusable rocket booster flyback sonic booms, which tend to have three distinct shocks and, like aircraft, also have durations of a few tenths of a second (Anderson *et al.*, 2024c; Anderson and Gee, 2025b; Gee *et al.*, 2024b). Additionally, the launch-ascent sonic boom overpressures are 4–10 times higher than can be accounted for by vehicle geometry alone (Holloway *et al.*, 1973). Overall, these launch-ascent sonic boom waveforms resemble blast waves produced in free-field explosions (Esparza and Baker, 1977) and shock tubes (Tasissa *et al.*, 2016), though those waves tend to have durations around two orders of magnitude less than launch-ascent sonic booms.

Early researchers hypothesized that the exhaust plume was critical for understanding the launch-ascent sonic boom waveform shapes (Hilton *et al.*, 1972). At high altitudes, the ambient air pressure

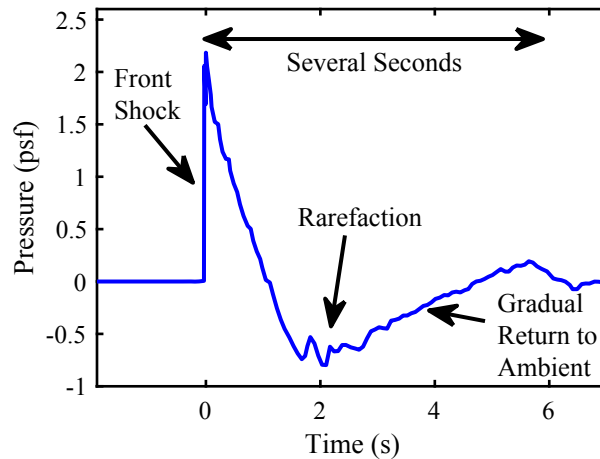


Figure 11.1 Annotated prototypical waveform showing the four waveform properties that are reproduced in this chapter. The waveform, from Henderson and Hilton (1974a), was measured 92 km from the launch site. A secondary arrival appearing 20 seconds after the front shock is not shown here.

decreases, and the exhaust plume balloons outward. This large, underexpanded exhaust plume (Alden and Habert, 1964; Franquet *et al.*, 2015) was thought to act as an effective body that dramatically increased the size and length of the rocket, greatly impacting the sonic boom shape and amplitude. However, the early researchers were only partly able to test this hypothesis because the plume models required for full-waveform modeling were too large for their available wind tunnels (Hicks and Mendoza, 1973b).

Current sonic boom modeling tools do not have accurate near-field signatures for launch-ascent sonic booms. This stems partly from the fact that such tools have historically been designed for traditional aircraft sonic booms and attention is only beginning to pivot toward rockets. For example, NASA's PCBoom 7.5.0 (Lonzaga *et al.*, 2022, 2025) software uses a combination of the Carlson (1978) equivalent N-wave and the Tiegerman (1975) hypersonic sonic boom estimation techniques, neither of which is capable of predicting the correct negative phase and gradual return to ambient observed in measurements. Although these models together may reproduce measured ground overpressures, the rest of the waveform is not accurately modeled. Because some applications require full waveforms, like predicting dynamic structural responses (Cheng and Benveniste, 1969; Clarkson and Mayes, 1972), prediction of full waveform shapes is an important element of rocket sonic boom research.

This chapter's purpose is to demonstrate that all four key characteristics shown in Fig. 11.1 naturally arise when modeling the sonic boom using a vehicle-plus-plume geometry with a sufficiently long plume. The key difference between the work here and previous launch-ascent sonic boom modeling efforts is that the constraint on plume length is removed by adopting a fully computational approach. Section 11.2 contains a brief discussion of underexpanded exhaust plumes followed by a review of the limited measurements and modeling performed during the Saturn V and Space Shuttle

eras. In Sec. 11.3, the ground signature in the carpet region is modeled using F-function methods and propagation via the Burgers equation. The effects of focusing are discussed in Sec. 11.4, where the ground signature from Sec. 11.3 is transformed to produce realistic waveforms at the focus and slightly downrange of the focus. Conclusions are then presented in Sec. 11.5.

11.2 Review of Historical Efforts

11.2.1 Exhaust Plumes

A photograph showing an underexpanded exhaust plume from a Saturn V rocket is shown in Fig. 11.2(a), complete with brighter and darker regions representing the shock and expansion waves expected inside an underexpanded plume (Peters and Phares, 1976; Franquet *et al.*, 2015). It is important to note that this image shows only the afterburning portions of the plume, but there are other, less-visible gases in the plume. Fig. 11.2(b) shows a Saturn V model with a large solid-body exhaust plume model used for wind tunnel testing. The fact that a solid body can be used to represent the exhaust plume in sonic boom studies was demonstrated by Hicks and Mendoza (1973a). Note how large the exhaust plume can be compared to the vehicle dimensions. Lastly, these exhaust plumes can be very long, as shown in Fig. 11.2(c). In this case, much more of the plume is visible because this SpaceX Falcon 9 rocket launched shortly after sundown, causing sunlight to scatter off the exhaust gases and become easily visible when viewing from the darker areas below. This particular photograph was taken when the vehicle was around 60 km in altitude, where the 75.8 kPa exit pressure from a single Falcon 9 engine (Mathews *et al.*, 2021) well exceeds the ambient pressure of about 20 Pa (NOAA *et al.*, 1976) and the plume is underexpanded. The exhaust plume expands outward after exiting the vehicle and then approaches a roughly constant-diameter cylindrical shape before ultimately decaying due to turbulence at large downstream distances. Even if some of the exhaust shown in this view is made visible by afterburning materials, afterburning in underexpanded plumes tends to be concentrated in the mixing layer (Viswanath *et al.*, 2005; Zhou *et al.*, 2020) which, to an approximation, represents the plume surface for sonic boom purposes (Hicks and Mendoza, 1973a). Although it is difficult to say how long the plume is in subplot (c), an approximate scaling based on vehicle base diameter indicates that the visible plume is on the order of 1.5 km.

11.2.2 Measurements

Aside from some infrasound observations of rocket sonic booms (Cotten and Donn, 1971), the first launch-ascent sonic boom measurements were made by Hilton *et al.* (1972) during the Apollo 15 mission using NASA's Saturn V rocket. They made measurements aboard ships at 87 and 970 km downrange from the launch site. Their final measured waveforms showed the non-N-wave shapes later verified by other measurements. Additionally, the sonic boom amplitude and duration were both greater than could be explained by vehicle geometry alone, leading them to the conclusion that both the amplitude and duration were controlled by the large underexpanded exhaust plume. The

gradual signature closure was hypothesized to be caused by the plume, a phenomenon that has been observed on a smaller scale and to a lesser extent in X-15 tests (Green and Putnam, 1974).

Similar measurements were performed during the Apollo 16 (Henderson and Hilton, 1974a) and Apollo 17 (Henderson and Hilton, 1974b) missions. Waveforms from each measurement location for Apollo 15-17 are shown in Fig. 11.3. Because all flights used the same vehicle and had similar trajectories, it is reasonable to view them all together for the sake of qualitative discussion, remembering that differences due to precise trajectory, weather, and measurement location are expected. The measurement at 63.8 km is described by Henderson and Hilton (1974b) and Holloway *et al.* (1973) as being in the prefocus region upstream of the actual focus based on the slower rise time. The subsequent measurements at 65 and 65.6 km are very near or right at the focus and have the highest amplitudes. The recordings at 66.3, 68, and 69 km show the single peak splitting into two peaks, with the second peak gradually moving farther away from the first peak. Such behavior is expected in the post-focus region because the primary, or “carpet” sonic boom arrives first and is followed by the wave reflected off the caustic (Hilton and Maglieri, 1966; Plotkin and Cantril, 1976;

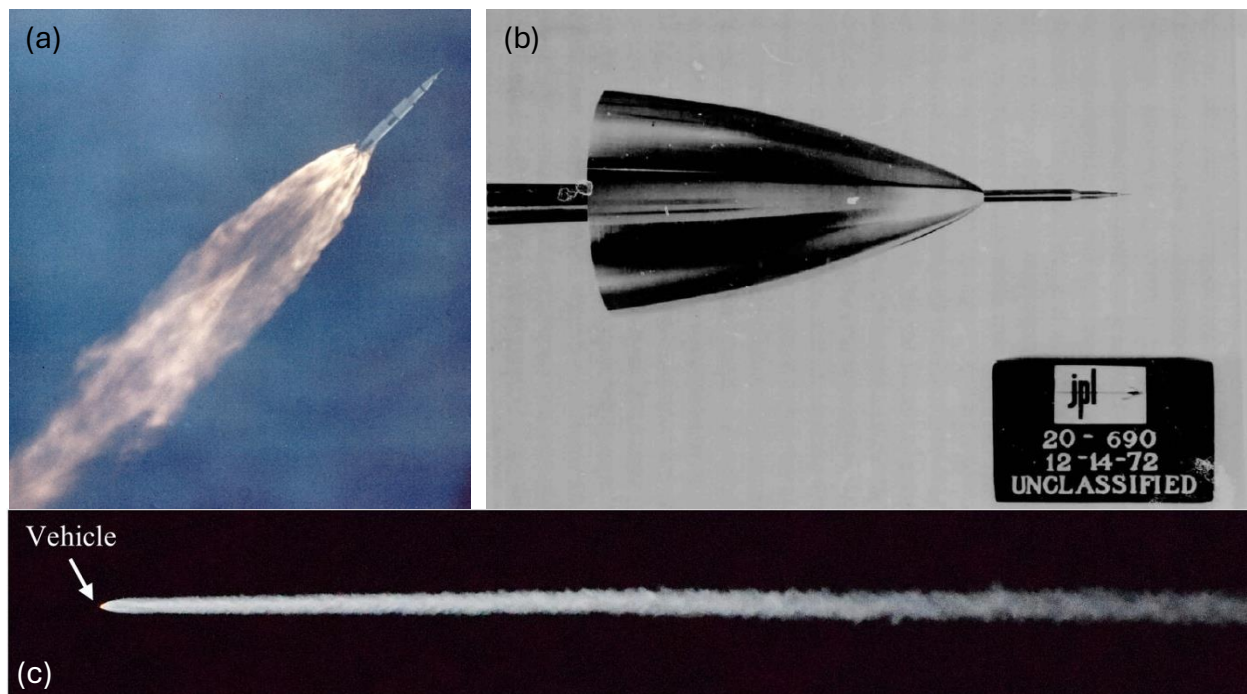


Figure 11.2 Examples of underexpanded exhaust plume shapes. (a) A photograph of a Saturn V during launch. Photo credit: NASA. (b) A model Saturn V with a solid-body exhaust plume model for wind tunnel testing, reproduced from Hicks and Mendoza (1973b). (c) A SpaceX Falcon-9 rocket during launch showing its long, underexpanded exhaust plume. The vehicle’s altitude was approximately 60 km. The exhaust gases are made visible far behind the rocket by the rocket launching shortly after sundown. Photo Credit: Ken Wong [Used with Permission].

Downing *et al.*, 1996; Maglieri *et al.*, 2014). For a useful illustration of sonic booms in the pre-focus, focus, post-focus, and carpet regions, the reader is invited to consider Fig. 3.10 in Maglieri *et al.* (2014). This trend persists at 85, 87, and 92 km, which show the secondary arrivals moving farther away from the carpet boom. It is expected that as these secondary arrivals move farther away, they also decay and ultimately disappear, leaving only the carpet boom. Lastly, the measurements at 130 and 970 km show booms that are far removed from the focus and thus clearly in the carpet region. Notably, at all locations where Saturn V sonic booms were measured, there is no evidence of N-wave formation.

Measurements were also made during Space Shuttle flights, and the results are similar. Specifically, measurements were made during the STS-5 (Garcia *et al.*, 1983b; Stanley, 2005), STS-7 (Stansbery *et al.*, 1983), and STS41-D (Stansbery and Stanley, 1984) launches. Although most of the reports are not publicly available, the thesis by Stansbery (1985) is available and the STS-7 report by Stansbery *et al.* (1983) was recently obtained via a Freedom of Information Act (FOIA) request by the author of this dissertation and may appear in publicly-available records in the future. In all cases, there is no evidence of N-wave formation, and the waveform shapes and trends resemble those for the Saturn V. Some additional information can also be found in the summary report by Maglieri *et al.* (2011).

11.2.3 Modeling

The first wind tunnel studies for Saturn V launch-ascent sonic booms were performed by Hicks *et al.* (1972b). This initial effort used 0.00337 (1:297) and 0.00168 (1:595) scale models between Mach numbers of 3.01–7.91. While they used conical plume shapes in this effort, Hicks and Mendoza (1973b) improved on this by using curved plume geometries like the one shown in Fig. 11.2(b). They found that this produced better peak overpressure predictions. Although a specific numerical criterion is not given, Hicks and Mendoza (1973b) also stated that the plume model needed to approach its asymptotic diameter before terminating to accurately determine the peak overpressure. They found that for most of their test conditions, a plume length of 1.5 vehicle body lengths was sufficient for peak overpressure prediction and that longer plumes tended to increase the signature duration rather than the overpressure. In all their test cases the abrupt plume model termination caused their final signatures to look much more like N-waves than like the measured launch-ascent sonic booms. As their primary goal was to model the signature's positive phase, this was acceptable at the time. Additionally, Hicks *et al.* (1972b) and Hicks and Mendoza (1973b) demonstrated that when the near-field pressure disturbances were more than half of ambient pressure, it was more appropriate to use a strong-shock propagation technique instead of other weak-shock methods. If a weak-shock method was used, the signature elongated faster and the overpressure decreased faster than was physically accurate, though the overall waveform shapes remained consistent. Additionally, Hicks *et al.* (1972b) caution that their strong-shock extrapolation technique may not be appropriate for portions of the signature far from the front shock.

Preparing for the Space Shuttle program, Holloway *et al.* (1973) used data from the Apollo program to create sonic boom models for blunt vehicles at high altitudes and Mach numbers. Among their findings was that the exhaust plume increased the sonic boom overpressure by a factor of 4–10,

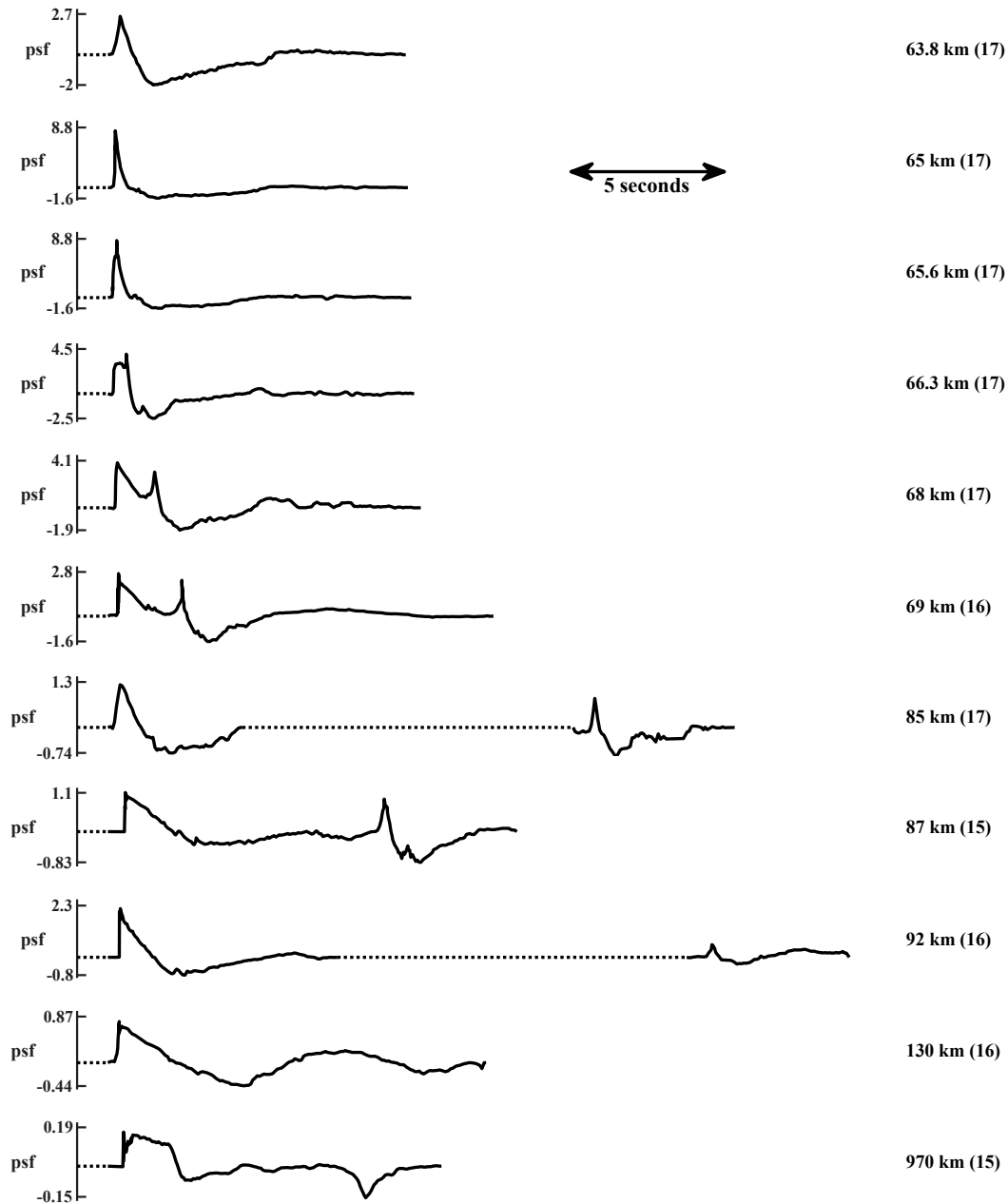


Figure 11.3 All Saturn V launch-ascent boom waveforms, digitized and compiled into a single figure for this chapter (Hilton *et al.*, 1972; Henderson and Hilton, 1974a,b). The distances from the launch site are shown on the right side of the plots along with the mission number (15-17) indicated in parentheses. Zero padding is indicated by dashed lines. For two cases (85 and 92 km), the zero padding in the center of the recording corresponds approximately to reported delays between the multiple arrivals. Amplitudes given in pounds per square foot (psf) (1 psf = 47.88 Pascals).

with higher factors associated with higher Mach numbers. This again highlights the importance of including the plume in launch-ascent sonic boom modeling, something that had been hypothesized since the first measurements on the Saturn V (Hilton *et al.*, 1972) and stated by others as discussed above.

Lastly, (Hicks and Mendoza, 1973a) demonstrated that an underexpanded gaseous plume can be accurately modeled using a solid body as long as the solid body follows the contours of the mixing boundary. Their experiments consisted of wind tunnel rocket models capable of emitting a gaseous nitrogen plume. Wind tunnel tests were performed at Mach 2.94 and 3.92. After measuring the near-field pressure signatures from the rocket geometries with the nitrogen plume, they used different plume models and found that the model shape following the turbulent mixing layer contour was most appropriate for reproducing the nearfield signature.

11.3 Methods

The goal in this section is to demonstrate that all the waveform properties annotated in Fig. 11.1 appear naturally when the vehicle-plus-plume geometries are used to model the ascent sonic boom. The four properties are the presence of a (1) front shock, (2) rarefaction, (3) gradual return to ambient, and (4) duration of several seconds. Because this chapter's purpose is to model the overall waveform shapes, without rigorous attempts to match specific measurements, several assumptions are made. These assumptions simplify the analysis while keeping the key phenomena at the forefront of the discussion. Many assumptions are discussed in the following subsections, and, in many cases, the effects are quantified in terms of peak overpressure and positive phase duration relative to the final result shown later in Fig. 11.7(b). To aid in communicating the workflow, Fig. 11.4 shows a block diagram indicating the steps taken throughout this modeling.

11.3.1 Geometry

Hicks and Mendoza (1973b) presented plume contours for the Saturn V launch vehicle. This approach enables the use of realistic plume contours while avoiding the need to re-calculate the exhaust flow properties. In their wind tunnel measurements, they used plume contours corresponding to different freestream Mach numbers between 3.01–7.29 and provided a table with the contour coordinates. However, as previously discussed, their plume contours were of finite length, with the longest plume being 2.5 times the vehicle body length, and all the others being only 1.5 times the vehicle body length. Thus, it is desirable to have a mathematical plume model that well-approximates their plume contours and then extrapolates smoothly to a maximum diameter (see Fig. 11.5), as observed in Fig. 11.1(c) (Alden and Habert, 1964; Andrews *et al.*, 1964; Raje *et al.*, 2017; Viswanath *et al.*, 2005; Zhou *et al.*, 2020). The plume contours can be approximated by

$$R(x) = \frac{a}{2} \left(1 - e^{-b(x^q)} \right) + R_0, \quad (11.1)$$

where $R(x)$ is the plume radius, R_0 is the initial plume radius, and a , b , and q are tunable parameters. The parameter a defines the asymptotic radius while b and q control the plume curvature. This

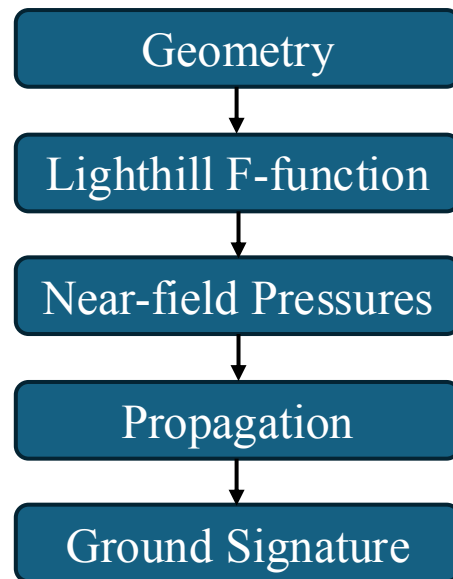


Figure 11.4 Block diagram indicating the modeling steps taken in these simulations.

model equation was chosen because it has the correct asymptotic behavior while being relatively simple and tunable to the plume contours given by Hicks and Mendoza (1973a), as shown in Fig. 11.5. Near the vehicle, the plume should be curved and, far from the vehicle, the plume should be approximately a constant diameter (Alden and Habert, 1964; Andrews *et al.*, 1964; Raje *et al.*, 2017; Viswanath *et al.*, 2005; Zhou *et al.*, 2020). For all the plumes in Hicks and Mendoza (1973b), it was found that setting $b = 0.007$ and $q = 1.0$ produced contours that well approximated the provided points. To provide an effective semi-infinite plume for this study, Eq. (11.1) is used out to 4 km behind the vehicle, with the vehicle and plume being sampled at intervals of about 1 m. It was found that further decreasing the sample interval resulted in only minor changes to the final signatures. The parameters matching each of their plume geometries are shown in Table 11.1 and a few examples are shown in Fig. 11.5.

According to Henderson and Hilton (1974b), the sonic booms first reaching the ground are generated around Mach 3–4 at an altitude of about 30–40 km. Thus, the plume model used for further analysis in this chapter is the Mach 3.51 condition, though it is worth noting that all the plumes produce simulated waveforms with similar overall shapes. The plume geometry is shown in Fig. 11.6(a) along with a rocket geometry that approximates the Saturn V height and diameter. As demonstrated by a variety of wind tunnel studies (Hicks and Mendoza, 1973a,b; Mendoza, 1975a) the front shock produced by the underexpanded plume quickly overtakes the shocks generated by the vehicle itself. Thus, it is not necessary to use a detailed rocket body geometry.

The flow field around the vehicle-plus-plume geometry is modeled using linearized supersonic flow theory. Although not as accurate as a full computational fluid dynamics approach, using linearized supersonic flow theory is justified by the fact that Carlson and Mack (1977) found that it can still predict far-field sonic boom properties for blunt geometries at high Mach numbers.

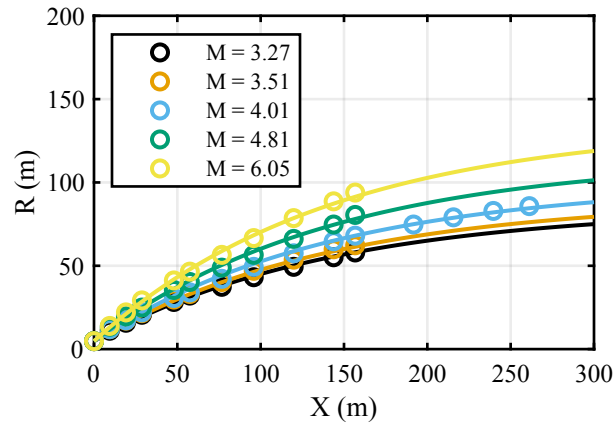


Figure 11.5 The tabulated (circles) and fared (lines) plume geometries for the first 300 meters behind the vehicle. Tabulated data are from Hicks and Mendoza (1973b) and the fared curves come from Eq. (11.1) with the parameters listed in Table 11.1. For one case, Mach 4.01, Hicks and Mendoza (1973b) defined the plume contours out to 2.5 body lengths.

Table 11.1 Plume model parameters to solve for $R(x)$ in Eq. (11.1). Values were chosen to approximate the plume contours provided by Hicks and Mendoza (1973b) and then to extrapolate smoothly out to a constant diameter.

Mach Number	a	b	q	R_0
3.01	150	0.007	1.0	4.79
3.27	160	0.007	1.0	4.79
3.51	170	0.007	1.0	4.79
4.01	190	0.007	1.0	4.79
4.25	195	0.007	1.0	4.79
4.56	205	0.007	1.0	4.79
4.81	220	0.007	1.0	4.79
5.02	230	0.007	1.0	4.79
6.05	260	0.007	1.0	4.79
7.29	320	0.007	1.0	4.79

The vehicle and plume geometries are shown in Fig. 11.6(a). Because the plume is an effective blunt body, it could be appropriate to create an effective geometry that better accounts for bluntness (Ritzel and Gottlieb, 1987; Gottlieb and Ritzel, 1988). For this chapter, a simple tangent cone correction was investigated, with the cone base attaching to the point on the plume where the slope exceeds the local Mach angle. The tangent cone correction changed the final ground signature (shown later in Fig. 11.7(b)) overpressure by -0.09% and positive phase duration by 0.52%. Because the effects were so small, such corrections were removed from this analysis. For larger exhaust plumes, it is possible that such corrections may become necessary.

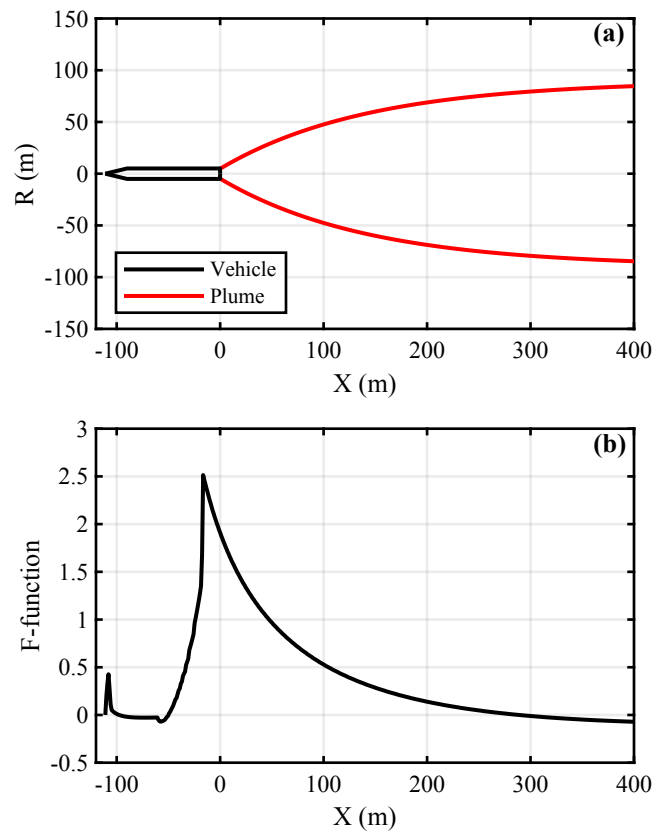


Figure 11.6 (a) The geometry used in this chapter to calculate the near-field pressure signature. The plume model from Eq. (11.1) are used to define the full extent of the exhaust plume. Near-field pressures are calculated by treating the vehicle and plume together as a single geometry. (b) The Lighthill F-function for the vehicle-plus-plume geometry shown in (a).

11.3.2 Lighthill F-function and Near-field Pressures

With a geometry defined, it is possible to calculate the near-field pressure ratio (Maglieri *et al.*, 2014)

$$\frac{p}{p_\infty} = \frac{\gamma M_\infty^2}{r_0^{1/2} \sqrt{2\mu}} F_L(x), \quad (11.2)$$

where p is the acoustic pressure, p_∞ is the freestream pressure, γ is the ratio of specific heats taken to be 1.4 in air, M_∞ is the freestream Mach number, $\mu = \sqrt{M_\infty^2 - 1}$, r_0 is the radial distance out to which the signature is linearly propagated, and $F_L(x)$ is the Lighthill F-function (Lighthill, 1948). Because γ can vary with temperature (Kestin, 1950), a smaller value of 1.3 was also tried (corresponding approximately to the exhaust temperature of 2600 K reported by Krider *et al.* (1974)) and found to change the overpressure by -4.0% and the positive phase duration by -3.2% relative to Fig. 11.7(b). As for the F-function, it is better to use the Lighthill F-function instead of the Whitham F-function (Whitham, 1952) for geometries that, like the effective body in Fig. 11.6(a), have slope discontinuities (see the Chapter Appendix for a comparison of the Lighthill and Whitham F-functions). While the Whitham F-function “blows up” at such slope discontinuities, the Lighthill F-function remains finite. In fact, Whitham (1952) discussed the Lighthill F-function and then made assumptions (including smooth geometry) that reduced the more-general Lighthill F-function to the more commonly used Whitham F-function. It has been argued that, in light of modern computational capabilities, the Lighthill F-function should always be used instead of the Whitham F-function (Ritzel and Gottlieb, 1987; Gottlieb and Ritzel, 1988; Jung *et al.*, 2015). The Lighthill F-function is written as

$$F_L(x) = \frac{1}{2\pi} \int_0^\infty \left(\frac{2}{\mu R(x)} \right)^{1/2} h \left(\frac{x - \bar{x}}{\mu R(\bar{x})} \right) dS'(\bar{x}), \quad (11.3)$$

where $R(x)$ is the body radius (assuming an axisymmetric body), $\bar{x}$ is a “dummy” variable of integration, h is a function that takes in the values in the subsequent parentheses, and S' is the first derivative of the cross-sectional area. Strictly speaking, this area should be evaluated using cross sections taken at the Mach angle (Whitham, 1952), but because the large blunt plume is expected to dominate the sonic boom generation, the cross sections are all taken at normal incidence in this chapter. The argument for this comes from Carlson and Mack (1977), who argue that, in the near field of a blunt body, the shocks are not angled at the Mach angle and therefore the more appropriate cross section is the normal one. The most difficult part of the Lighthill F-function calculation comes in evaluating the function $h(z)$, where z is any numerical input,

$$h(z) = \left(\frac{\pi}{2\zeta} \right)^{1/2} \frac{1}{K_1(\zeta)} H(z), \quad (11.4)$$

where ζ is Heaviside’s operator of differentiation (d/dx), K_1 is the modified Bessel function of the second kind, and $H(z)$ is the Heaviside step function. Fortunately, the end user need not calculate $h(z)$ from Eq. (11.4), as for $z > 4$, $h(z) \approx 1/\sqrt{2z}$ and for $-1 \leq z \leq 4$, Ritzel and Gottlieb (1987) tabulated values in increments of 0.5, which are then easily interpolated. For $z < -1$, $h(z) = 0$.

Figure 11.6(b) shows the Lighthill F-function for the vehicle-plus-plume geometry shown in Fig. 11.6(a). The first peak, just before -100 m, corresponds to the rocket nose while the second, much larger peak, corresponds to the onset of the exhaust plume. Similar near-field qualities, like the small nose shock followed by a much larger plume-induced shock, have been demonstrated in wind tunnels using gaseous plumes (Hicks and Mendoza, 1973a).

11.3.3 Propagation and Ground Signature

The pressure signature corresponding to the geometry and F-function in Fig. 11.6 is shown in Fig. 11.7(a). This signature was calculated via Eq. (11.2) with $r_0 = 395$ m, which is the same relative distance as the wind tunnel measurements of Hicks and Mendoza (1973b). The sonic boom is assumed to propagate orthogonally to the wavefronts, which are assumed to be angled at the Mach angle $\theta = \sin^{-1}(1/M_\infty)$ (Lonzaga *et al.*, 2022). Geometrically, this means that wave fronts are closer together by a factor of M_∞ along the propagation direction. To account for this,² the pressure distribution length scale at r_0 is divided by M_∞ . To convert the pressures from the spatial coordinate x into temporal coordinates, the x values were divided by the assumed speed of sound of 302 m/s at 30 km altitude (NOAA *et al.*, 1976) and sampled to a 1 kHz sample rate. If a higher sample rate of 10 kHz is used, the final overpressure changes by 0.10% and the positive phase duration by 0.63%, indicating that a lower sample rate of 1 kHz is acceptable. After completing these steps, the signature was ready for propagation to the ground.

Because long-range, high-amplitude shock propagation through the atmosphere is a complex affair, there are some additional assumptions requiring justification. These are discussed over the next few paragraphs, where it is argued that these assumptions do not affect the conclusions in this chapter. First, the peak overpressure ratio of 0.85 shown in Fig. 11.7 is higher than the value of 0.4 measured by Hicks and Mendoza (1973b). It is possible that at least part of this discrepancy can be explained by the fact that the pressures in this chapter have been linearly propagated to the distance r_0 while the wind tunnel measurements experience full nonlinear evolution up to this distance. In the linear theory, the pressure amplitude decays as $r_0^{1/2}$ in Eq. (11.2). If this term is replaced with $r_0^{3/4}$, the characteristic decay rate for a cylindrically-spreading weak shock (Maglieri *et al.*, 2014; Hamilton and Blackstock, 2024; Landau and Lifshitz, 1987), then the overpressure ratio at r_0 decreases to 0.19, much less than the measured value of 0.4 by Hicks and Mendoza (1973b). However, it is known that weak-shock theory tends to underestimate waveform overpressure in the near-field for rocket ascent sonic booms (Hicks *et al.*, 1972b; Hicks and Mendoza, 1973b), so the correct overpressure ratio likely lies somewhere between 0.19 and 0.85, which is where the wind tunnel measured data of 0.4 exists. If the signature is scaled to match the overpressure ratio of 0.19 predicted using $r_0^{3/4}$, then the overpressure for the final propagated signature on the ground (see Fig. 11.7(b)) changes by -58% and the positive phase duration by -45%. If instead the signature at r_0 is manually scaled to match the overpressure ratio of 0.4 measured by Hicks and Mendoza (1973b), the final overpressure changes by -34% and the positive phase duration

²Per personal correspondence with Dr. Joel Lonzaga of NASA Langley Research Center, this same scaling methodology is used in PCBoom.

by -27%. In both cases, the overall waveform shape remains consistent. Ultimately, to minimize manual adjustments to the simulations, the linearly propagated amplitude of 0.85 at r_0 was used to produce the near-field pressures in Fig. 11.7(a). As will be seen throughout the remainder of the paper, this near-field overpressure scaling represents the largest uncertainty in terms of changing the overpressure and positive phase duration. Fortunately, because the waveform shapes remain consistent, the conclusions are not greatly impacted by this. However, obtaining accurate near-field amplitudes is one of the first steps that should be taken when improving on these results.

Second, because the starting pressure signature in Fig. 11.7(a) has overpressure ratio values higher than 0.5, the strong shock extrapolation technique of Hicks *et al.* (1972b) should arguably be used out to the distance where the overpressure ratio drops below 0.5. Based on the work of Hicks and Mendoza (1973b), weak shock assumptions tend to overestimate how rapidly the waveform evolves. Assuming that linear propagation would underestimate waveform evolution, the strong shock propagation effects should lie somewhere between the linear and weak shock models. Thus, to bound the error induced by using weak shock assumptions in the relatively short distance range where the overpressure ratio exceeds 0.5, a test case was run with a farther r_0 of 1,150 m. At this distance the linearly propagated overpressure ratio from Eq. (11.2) drops below 0.5 and Hicks *et al.* (1972b) state that weak shock assumptions can be used. This process resulted in an overpressure difference of 8.3% and a positive phase duration difference of -6.5 % relative to the results in Fig. 11.7(b), which use the original $r_0 = 395$ m. Thus, if strong shock assumptions were used in the region where the overpressure ratio exceeds 0.5, the difference in final signature would be on the order of a few percent while the final waveform's overall shape would be consistent.

Lastly, no atmospheric raytracing is performed in this chapter. Despite the fact that raytracing will be an important part of future work, the complexity involved is beyond the scope of this chapter. Although NASA's PCBoom software (Lonzaga *et al.*, 2022) could be used for raytracing and propagation, it has primarily been validated on traditional aircraft at lower altitudes than rockets. Additionally, its closed-source nature means that the user does not have much control or definite knowledge of the algorithms being used. Therefore, to preserve full control and knowledge over the methods in this chapter, and because the goal is to demonstrate overall waveform properties, PCBoom is not used.

The source waveform in Fig. 11.7(a) is nonlinearly propagated via the Generalized Burgers Equation for cylindrical spreading (Hamilton and Blackstock, 2024),

$$\frac{\partial p}{\partial r} = \frac{\beta}{2\rho_0 c_0^3} \frac{\partial p^2}{\partial \tau} + \bar{\Psi}p - \frac{1}{2r}p, \quad (11.5)$$

where r is the radial distance from the source, β is the coefficient of nonlinearity taken to be 1.201 in air, ρ_0 is the local ambient density, c_0 is the local ambient speed of sound, τ is the retarded time, and $\bar{\Psi}$ is an operator acting on the pressure p that accounts for atmospheric absorption and dispersion. This equation is solved using the same hybrid time-frequency approach described in Gee (2005) and Gee *et al.* (2008) and applied in Anderson and Gee (2025b) for rocket flyback sonic booms. The starting signature was propagated from an altitude of 30 km. For simplicity in the absence of raytracing software for this analysis, straight vertical propagation to the ground is

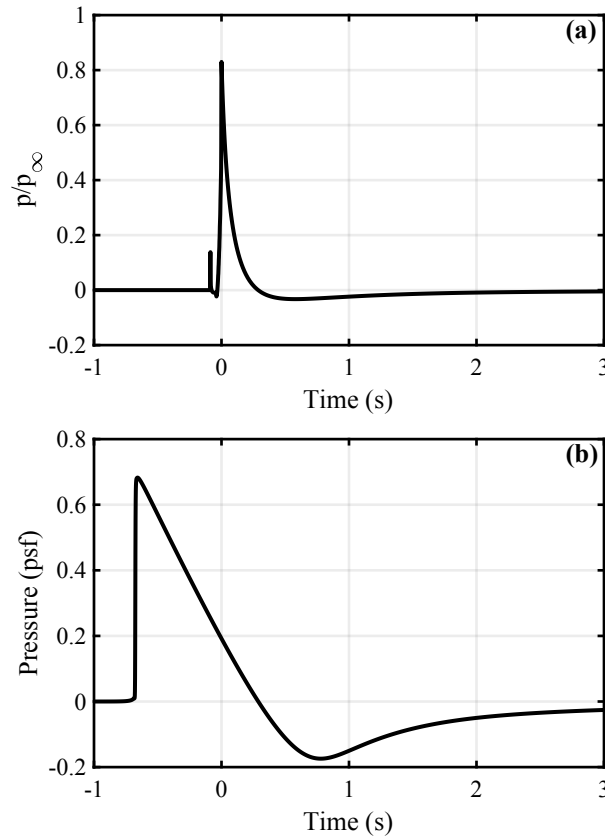


Figure 11.7 (a) The near-field signature at a distance of $r_0 = 395$ m. (b) The final propagated signature at ground level. The time axes are constant between the two subplots to indicate the amount of shock movement due to nonlinear propagation.

assumed. The ambient values ρ_0 and c_0 were regularly updated according to propagation altitude. When the signature reached 0 km, a ground reflection factor of 1.9 was applied, common in sonic boom research (Lonzaga *et al.*, 2022).

The final propagated signature at the ground is shown in Fig. 11.7(b). The peak overpressure is 0.68 psf, while most of the non-focus signatures shown in Fig. 11.3 have overpressures on the order of 1–3 psf. Thus, the modeled overpressure here is somewhat lower than would be anticipated. This could be due in part to the assumption of straight-ray propagation with cylindrical spreading. As an extreme example, if no geometric spreading were assumed (i.e., plan wave propagation), the overpressure on the ground would be 3.6 psf and the positive phase duration would increase by 64% relative to Fig. 11.7(b). As for the signature duration in Fig. 11.7(b), the modeled signature is a full order of magnitude longer than a typical aircraft sonic boom, as was expected. However, it is not quite as long as the measured signatures in Fig. 11.3, though this is difficult to quantify as the signature closes only asymptotically. This could be related to the plume extrapolation performed via Eq. (11.1). While Eq. (11.1) successfully approximates the plume contours given by Hicks and

Mendoza (1973b) out to the 1.5 body lengths they provide for most plumes (and out to 2.5 body lengths for their single longer plume), it may not fully represent the plume shape behind it.

Although the modeled signature in Fig. 11.7(b) is not a perfect match to the measured signatures, it has all the key properties sought in this investigation. Namely, the waveform has a (1) front shock, (2) rarefaction, (3) gradual return to ambient, and (4) duration of several seconds, as indicated previously in Fig. 11.1. This accomplishes the primary aim of this chapter, which is to demonstrate that these four characteristics could be replicated when including a longer plume geometry. Increased levels of detail in the modeling, especially for near-field pressures and stratified atmosphere effects, will help further improve agreement between model and measurement.

11.4 Focusing

Having successfully reproduced the “carpet” waveform shapes expected far from the focus (which is defined as being at the footprint onset), the waveforms at and downrange of the focus can now be modeled. Although a full analysis would require computationally expensive solutions to the lossy nonlinear Tricomi equation (Salamone *et al.*, 2013), a simplification can be made, justified by prior work (Taylor, 1980; Bishop *et al.*, 1988). Reflection off the caustic induces a 90° phase shift, which can be approximated by taking the imaginary part of the Hilbert transform. An example is shown in Fig. 11.8 for both (a) an N-wave and (b) the modeled launch-ascent carpet sonic boom from Fig. 11.7(b). While the transformation on the N-wave produces the well-documented U-wave (Plotkin and Cantril, 1976; Downing *et al.*, 1996; Maglieri *et al.*, 2014), the ascent boom transformation results in a signature that, after the initial exponential increase, resembles a fishing hook and may well be described as a “hook wave”.

These transformed signatures can be used to approximate anticipated waveform shapes near the focus region. At the focus, the carpet boom and the caustic-reflected boom arrive simultaneously and, to an approximation, superpose. This is demonstrated, using the signatures from Fig. 11.8(b), in Fig. 11.9(a). An increase in amplitude is also expected, determinable via ray-tube techniques. In previous studies (see Maglieri *et al.* (2014) for a summary of focusing studies), the increase in amplitude at a focus relative to the carpet signature is called the “focus factor” and typically has values on the order of 2.5–5 but can be as much as 9 or more. Because the current study does not implement any ray tube calculations, this focusing factor is omitted here and it is understood that while the shapes are expected to be similar, the amplitudes may not fully agree with measurements. Examples of measured focus booms during Apollo and Space Shuttle missions are shown in Fig. 11.9(b-d). The focus signatures tend to have tall, relatively narrow peaks followed by a rarefaction and gradual return to ambient. In several ways they are similar to the carpet booms, but the distinction tends to be a taller relative peak and a deeper relative rarefaction. In the post-focus region, the carpet and reflected booms arrive at different times, with the reflected boom arriving after a time delay that depends on distance from the focus but can be as long as 20 seconds in some cases (Henderson and Hilton, 1974a).

A post-focus waveform example created using the result from Fig. 11.7(b) is shown in Fig. 11.9(e) and measurements are shown in Fig. 11.9(f-h). The time delay between the two arrivals depends on

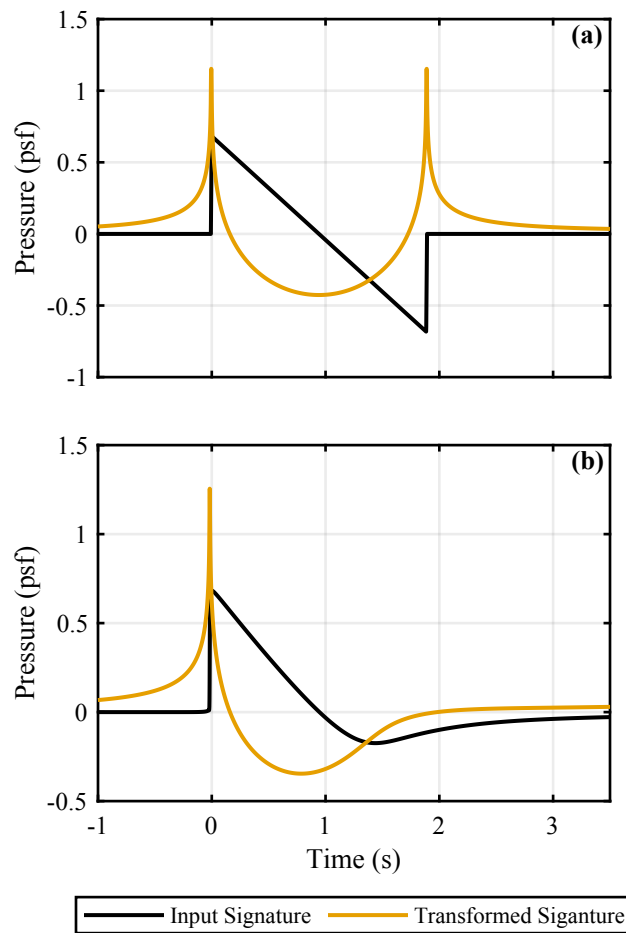


Figure 11.8 An input and Hilbert-transformed signature for both an (a) N-wave and (b) the simulated launch-ascent carpet sonic boom.

distance from the focus and is ordinarily determined with rigorous raytracing techniques. However, because raytracing was not used in this chapter, the offset in Fig. 11.9(e) was manually chosen to approximate the delays observed in the measurements. The agreement in overall shape between the simulated and measured sonic booms is remarkable. Each signature begins with an initial shock followed by a decrease in pressure, then an upturn that leads into a secondary peak of comparable or greater amplitude than the first. Following the second peak, a deep rarefaction occurs that in some cases is comparable in amplitude to the initial shock. After this rarefaction, the pressure gradually returns to ambient values. Lastly, as distance from the focus increases, the reflected boom ultimately decays to ambient pressure, leaving behind only the carpet boom. The simulated carpet boom from Fig. 11.7(b) is reproduced here in Fig. 11.9(i), along with measured carpet signatures in Fig. 11.9(j-l). Because most historical measurements have been made near the focus region, some of the measured waveforms still had a reflected wave that occurred outside the time limits

used in Fig. 11.9. Each shape shows a sudden pressure rise on the order of 0.7–2 psf followed by a rarefaction of smaller amplitude than the initial peak and then a gradual return to ambient conditions, with each signature lasting 4–8 seconds.

11.5 Conclusions

Sonic booms from ascending rockets have unique waveform characteristics not observed with traditional aircraft sonic booms, or even with reusable rocket flyback sonic booms. The typical waveform shape in the carpet region resembles an elongated blast wave, consisting of a (1) front shock, (2) rarefaction, (3) gradual return to ambient, and (4) duration of several seconds. These waveforms have been observed to last a full order of magnitude longer than traditional aircraft sonic booms, persisting for several seconds instead of a few tenths of a second.

In this chapter, the first full-waveform simulations for rocket ascent sonic booms have been performed. While previous studies in the 1970–80s were limited by the practical constraints of including large plume models in wind tunnels, the approach in this chapter is fully computational. The plume model in this chapter was designed to approximate a plume model used by earlier researchers (in their wind tunnel studies) and then was smoothly extrapolated out to lengths that were not practical for wind tunnel testing. Modeling the plume out to larger distances enables the determination of the signature's negative phase. The near-field signature was determined via the Lighthill F-function, which allows for slope discontinuities, and propagation was performed using the Generalized Burgers Equation with cylindrical spreading. The final propagated signature has all the desired waveform shape characteristics, demonstrating that the peculiar waveform shapes measured on the ground arise naturally when the modeled plume is long enough to allow for the full rarefaction to develop.

The predicted sonic boom waveform on the ground was also transformed into a caustic-reflected wave, representative of what occurs near the focus. This was used to produce simulated waveforms at the focus, in the post-focus region, and in the carpet region, with favorable shape comparisons to measured data.

Based on these results, a summary explanation for the waveform shapes is given here. The large, underexpanded exhaust plume dominates the sonic boom formation. The blunt plume creates a bow shock much stronger than the shock produced by the rocket body. Because the plume has no clear termination, the negative phase of the signature returns so gradually to ambient that no tail shock is able to form. Additionally, the large plume results in a sonic boom with a duration of several seconds. The final signature resembles an elongated blast-like wave with the aforementioned properties. In the focus region, secondary arrivals of caustic-reflected signatures superpose on the primary waveform and produce signatures with multiple peaks. In some cases, the second peak can be higher than the first.

The next research steps for launch-ascent sonic boom modeling include applying these plume and near-field models in PCBoom or other raytracing software, where stratified atmosphere effects, including geometric spreading and focusing, are likely to be better accounted for. It is possible that this will resolve the discrepancy between simulated and measured pressure amplitudes or at

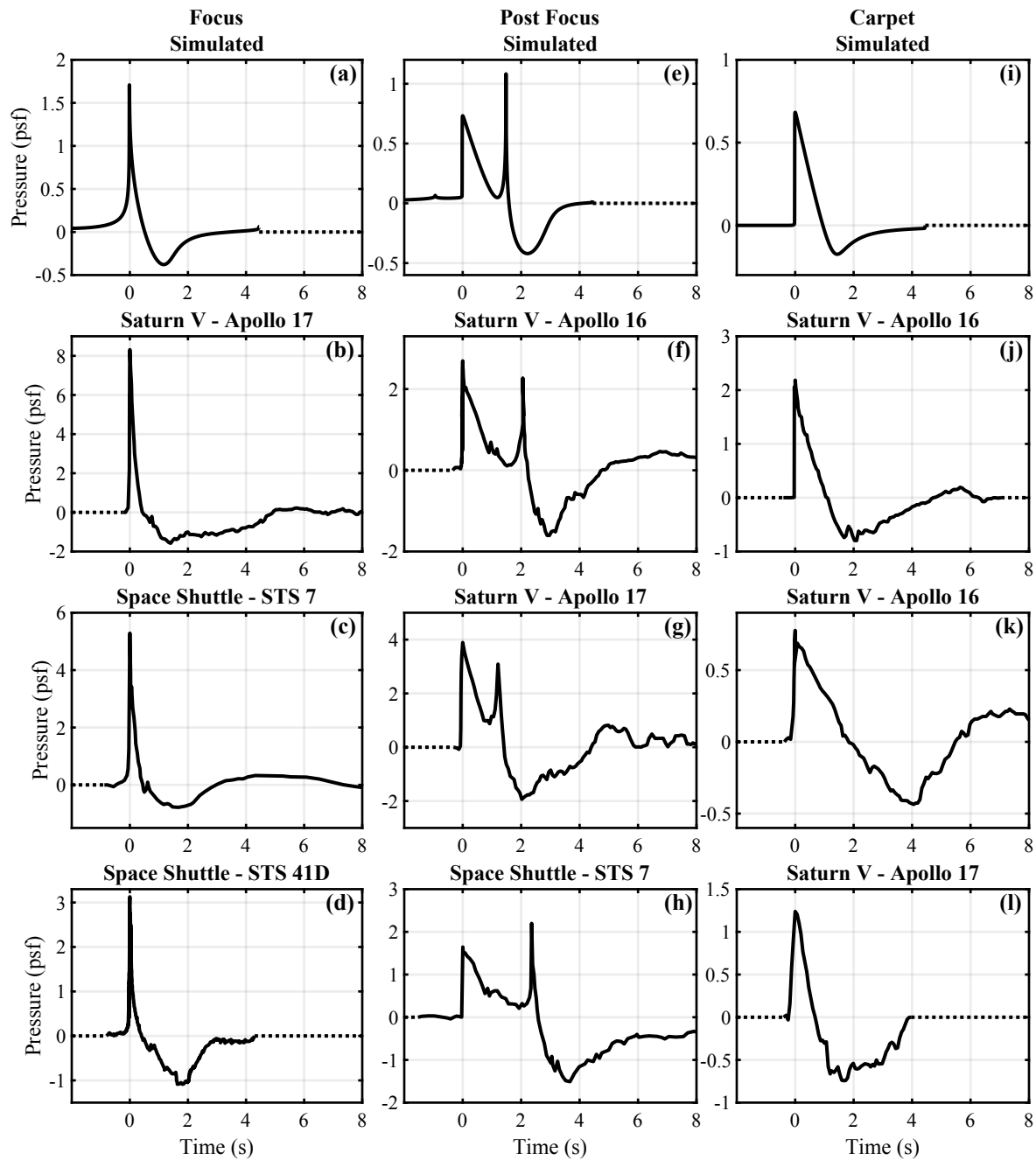


Figure 11.9 Simulated and measured booms at the focus (a-d), in the post-focus region (e-h) and in the carpet region (i-l). Apollo 16 and 17 data come from Henderson and Hilton (1974a) and Henderson and Hilton (1974b) and STS 7 and 41D data come from Stansbery *et al.* (1983) and Stansbery (1985) respectively.

least indicate possible future directions for research into amplitude matching. Future work also necessitates accurate measurements from a variety of rockets flying at different altitudes so that plume effects can be accurately modeled. Finally, an accurate assessment of how to model such a long underexpanded exhaust plume that gradually becomes turbulent will contribute to more accurate models. All of these improvements will contribute to a better understanding of the types of features expected in launch-ascent sonic boom signatures from future launch vehicles.

Acknowledgements

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11.6 Chapter Appendix: Lighthill vs Whitham *F*-functions

Whitham (1952) presents two *F*-functions in his paper. The first was derived by Lighthill (1948) and is valid for slender bodies with slope discontinuities. The second is a simplified version of the Lighthill *F*-function that is valid for slender bodies that are smooth. This simplified version became known as the Whitham *F*-function. These two *F*-functions are compared in Fig. 11.10 for three example geometries provided by Whitham (1952). Subplot (a) shows a pointed, semi-infinite geometry that is somewhat similar to the exhaust plumes modeled in this chapter. The two *F*-functions have similar shapes, with a positive phase followed by a shallow rarefaction and gradual return to ambient. Although the *F*-function curves are similar, they are not expected to be identical. Subplot (b) shows a finite curved geometry. The two *F*-functions again start out with a positive phase followed this time by a deeper rarefaction than in (a) and conclude with a sharp return to positive values and a gradual return to ambient. Finally, subplot (c) shows the 5-10 calibre ogival head bullet used as a detailed example in Whitham (1952). For this example, he states that, because there are slope discontinuities, the Lighthill *F*-function must be used. The Lighthill *F*-function shown in subplot (c) matches the results shown by Whitham (1952). The Whitham *F*-function is also included in subplot (c) to demonstrate that it misplaces the shocks and overestimates amplitudes for geometries with slope discontinuities.

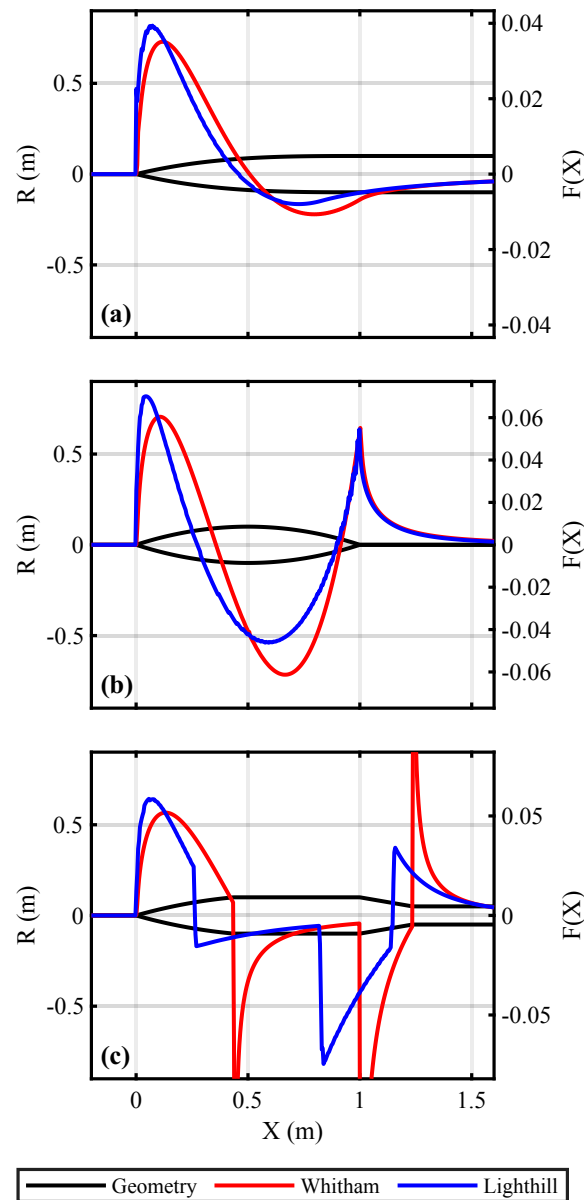


Figure 11.10 Comparisons of the Whitham (1952) and Lighthill (1948) F -functions using three example geometries from Whitham (1952). The subplots (a), (b), and (c) correspond to examples C, D, and E in Whitham (1952). Note that, to match the geometry Whitham (1952) shows in his example D, the equation he provides must be scaled vertically by a factor of 4. (This figure is identical to Fig. 9.15 shown previously in this dissertation.)

Chapter 12

Conclusion

This dissertation work has been focused on sonic booms from rockets. This research comes at a time when the global launch cadence is rapidly increasing, a trend that is supported in part by reusable rocket technology. The increase in launches and reusable rocket landings is leading to more rocket-produced sonic booms. Because such sonic booms may have impacts on surrounding communities, infrastructure, and wildlife, this dissertation is both useful and timely.

In Chapter 2, historical studies on rocket and spacecraft sonic booms have been compiled into a thorough literature review. Because the bulk of these studies were performed during the Apollo and early Space Shuttle programs, much of it has been forgotten or unnoticed by the global sonic boom community. By bringing these earlier efforts back into focus, this review provides a genuine contribution to the global sonic boom community as more attention turns to rocket sonic booms. Additionally, this literature review has led to the public release of several previously-inaccessible historical documents with important research results. To maximize overall impact, the contents in Chapter 2 are anticipated to serve as the basis for a comprehensive article on the history of spaceflight-induced sonic booms.

Because reliable research depends on reliable data, Part I of this dissertation was focused on sonic boom measurement and processing techniques. While this work was performed as part of the NASA X-59 Quiet Supersonic Transport (QueSST) program, the measurement and analysis methods are largely the same for rocket sonic booms. Because sonic boom measurements are often contaminated with high-frequency noise either from hardware or ambient conditions, metrics designed to estimate human perception can easily be inflated. This is especially true for the “low booms” expected from the X-59 and those observed at far distances from rockets. This problem was solved in Chapter 3 by introducing methods for automatically filtering the sonic boom spectra based on signal-to-noise ratio requirements. The methods successfully removed contaminating noise both in simulation and experiment. Another issue, discussed in Chapter 4 is the influence of atmospheric turbulence on sonic booms. This research was focused on direct measurements of metric variability across an array of microphones. A method for placing uncertainty limits on standard deviation estimates was recommended to enable fair comparisons between simulations and measurements. Additionally, simulated statistical results using state-of-the-art models and inputs were compared with measurements, where it was found that the simulations did not agree well with

the measured data, opening the door to future studies to improve the modeling techniques. Finally, Chapter 5 contains an overview of suggested best practices for sonic boom measurement and analysis including zero padding amounts for smoothing low-frequency spectra, time-domain windowing, restoration of low-frequency spectral energy, and the effects of microphone elevation on sonic boom metrics. These best practices were derived from work by both the author of this dissertation and other collaborators, all working toward the accurate measurement and analysis of sonic booms.

In Part II, attention was turned to the sonic booms produced by reusable rocket boosters as they descend through the atmosphere toward their landing target. These “flyback” sonic booms on land are a relatively new phenomenon because rocket boosters have historically been discarded in the ocean, far from any observers. In Chapters 6–7, measurements from three flyback sonic booms from Falcon 9 rockets were presented. At distances greater than 2 km from the launch and landing locations, the sonic boom overpressures exceeded the peak pressures experienced during the launch. At distances farther than about 5 km, the sonic boom was found to result in almost as much sound exposure as the entire launch that preceded it. Additionally, the sonic boom perceived level (PL) exceeded the NASA X-59 low-boom target level of 75 dB out to at least 25 km from the landing location. And finally, the sonic boom metrics all plateaued within 2 km of the landing site. This result indicated that there is a zone of roughly-constant exposure around the launch pad with a radius of about 2 km, a result that may help determine future observer distance thresholds for rocket cargo applications.

The Falcon 9 booster’s flyback booms also present several unique physics problems. For example, while most aircraft produce sonic booms with N-wave shapes at the ground, the Falcon 9 booster’s flyback booms have a consistent triple-shock structure, referred to as the “triple boom”. Although potential explanations spanned vehicle maneuvers, exhaust plume effects, and landing leg or grid fin deployment effects, these were all found unnecessary in explaining the triple boom’s origin. In Chapters 8–9, it was demonstrated that the vehicle geometry alone can account for the triple sonic boom. The first shock originates from the engine section (which faces the oncoming air during descent), the middle shock comes from a combination of a rarefaction wave near the vehicle base and a shock wave produced by the grid fins, and the third shock is produced at the booster top as the geometry terminates and the pressure returns to ambient. This was demonstrated using sonic boom theory, computational fluid dynamics, nonlinear acoustic propagation, and photographic evidence. This result moves the sonic boom community a step closer to using improved rocket source functions in sonic boom modeling software, instead of the N-wave assumptions that have typically been used to-date.

Part III of this dissertation was devoted to rocket launch-ascent sonic booms. These sonic booms, produced during the launch phase, typically reach the surface out at sea, far from observers. However, recent trajectory changes have resulted in launch-ascent sonic booms on land in Southern California. Because the sonic boom levels were found to vary seasonally, it was hypothesized that the seasonal weather changes caused the variation across seasons. This was proved in Chapter 10. In this work, a simulated launch trajectory along the coast was coupled with daily meteorological data spanning six years. The resultant sonic boom footprints agreed well both with specific measurements and with the seasonal trends. A seasonal shift between easterly and westerly winds was identified as the key factor in moving the sonic boom footprint. Using these results, a path forward described

as “Strategic Seasonal Launch Scheduling” was presented as a possible means by which launch providers could launch all their missions each year while simultaneously reducing sonic booms on land. The premise is that trajectories with coastal launch trajectories can be strategically scheduled for the summer months, when the easterly wind reduces the probability of sonic booms over large land areas. The other trajectories, farther from the coast, can be primarily launched in the remaining months. If launch schedules can be flexible enough, this strategy may substantially reduce the launch-ascent sonic booms on land.

Similar to the flyback booms discussed in Part II, the launch-ascent sonic booms studied in Part III have unique waveform characteristics. These waveforms are neither an N-wave nor a triple boom. Instead, launch-ascent sonic booms tend to be shaped like long blast waves with a (1) front shock, (2) rarefaction, (3) gradual return to ambient, and (4) duration of several seconds. Although this was noticed by researchers during the Apollo and Space Shuttle programs, it was never fully explained. While they hypothesized that the large underexpanded exhaust plume at high altitudes controlled the sonic boom shape, they were only able to completely model the positive phase portion because plume models of sufficient length were deemed too large for their wind tunnels. In Chapter 11, the full waveform shape was successfully modeled by using a simulated semi-infinite plume. Instead of being constrained by wind tunnel dimensions, this analysis was carried out numerically by using sonic boom theory and nonlinear acoustic propagation. The final signatures have all four characteristics listed above. Using simplified focus-boom modeling methods, it was also demonstrated that the multi-peaked waveforms frequently measured near the focus region naturally arise when simulating reflection off a caustic. Successfully modeling these waveform shapes marks an important step forward in launch-ascent sonic boom modeling right as more rockets are being launched closer to coastlines.

Future Work

Although this dissertation work has taken many important steps forward in the emerging field of rocket sonic booms, there remains much work to be done. Although several measurement and analysis procedures were laid out in Part I, there are no universal standards for making sonic boom measurements and there are still questions about how to remove other noise sources, how much variability to expect from atmospheric turbulence, and how to best configure hardware in the field. For rocket booster flyback sonic booms, initial measurements have now been made and published, but several important physics questions remain. For example, there is no evidence in the measurements shown in Part II that the waveform shock locations or signature durations evolve at all with distance from the landing location, contradicting expectations that sonic booms should elongate with propagation distance. Similarly, there is no evidence in any of the measurements shown in this dissertation that the triple sonic boom merges into an N-wave with sufficient propagation distance. Additionally, although the triple sonic boom phenomenon has been modeled, the waveform amplitudes and durations do not align with measured signatures. For the rocket ascent sonic booms discussed in Part III, seasonal trends have only been determined for a single launch location and trajectory. While this is an important step forward, many more trajectories and weather patterns

need to be modeled and measurements need to be made to determine whether strategic launch scheduling is a viable solution. And lastly, the waveform modeling needs to be implemented in full sonic boom raytracing software to further improve on the waveform shapes and determine areas for improvement.

To be concrete, the next steps for the research on rocket sonic booms should include:

- Standardize measurement and signal processing approaches so that comparisons between research teams can be accurately made.
- Study the effects of atmospheric turbulence on rocket sonic booms and compare the results to sonic booms produced by other sources, like traditional aircraft.
- Perform detailed computational fluid dynamics simulations and wind tunnel testing on reusable booster geometries and propagate those near-field signatures to the far field. This will resolve some remaining questions about how each geometry component contributes to the final sonic boom waveform.
- Obtain measurements of flyback sonic booms from new reusable rocket boosters as each design starts flying. Doing so will demonstrate the degree to which the models developed for one rocket are applicable to others.
- Collect launch-ascent sonic boom data undertrack using modern measurement methods. This can be done at the Channel Islands, where the sonic booms may be relevant for wildlife.
- Use computational fluid dynamics to determine shock strengths and rarefaction details for sonic booms produced by rockets with underexpanded exhaust plumes.
- Study the effects of rocket sonic booms on humans. While NASA is doing this with aircraft sonic booms through the X-59 program, the waveform shapes for rocket sonic booms are different enough that the X-59 results might not directly translate over.
- Perform optimizations on both trajectory and vehicle design to determine the degree to which rocket sonic booms can be optimized.
- Use raytracing software coupled with meteorology and a variety of trajectories to determine whether rocket sonic boom mitigation through seasonal launch scheduling is a viable path to pursue.
- As reusable upper stages for rockets begin producing sonic booms on land during reentry, perform measurements and simulations similar to those in this dissertation to determine waveform shapes, amplitudes, and trends.

Overall, this dissertation work represents a useful and timely step forward in spaceflight-related sonic boom research. Measurement and analysis methods have been presented, important new trends have been discovered, and physics questions about waveform shapes have been addressed. Although more work remains to be done, this dissertation establishes a foundation for future research and modeling efforts in the growing field of rocket sonic booms.

Appendix A

Measuring the Frequency-dependent Directivity and Sound Power of Rockets During Launch

Abstract

¹With the increasing global rocket launch cadence, there comes a greater demand to understand how rocket noise might impact local environments, communities, and structures. Far-field acoustic levels are typically estimated through simplified models, which rely on accurate noise source characteristics. This chapter provides methods for educing the noise directivity, sound power, and acoustic efficiency of rockets using ground-based acoustical measurements and three-dimensional trajectory. Radiation in the forward hemisphere, ground reflections, and propagation losses are considered. As a detailed example, source quantities are calculated from noise data collected during two United Launch Alliance Atlas V 401 rocket launches. Averaging over multiple measurement locations, the Atlas V had a peak radiation angle of 66–68 degrees and a peak directivity index of 4.8 dB. With a radiated OAPWL of 192.1–193.9 dB (193.0 dB if using the energy-averaged directivity) the Atlas V’s acoustic efficiency was 0.28–0.42%. (0.34% if using the energy-averaged directivity). These methods are used to produce refined estimates of sound power level and acoustic efficiency from other rockets, including the Space Launch System and Delta IV Heavy launch vehicles. With confirmed consistency in measurement techniques and calculation methods, acoustic efficiency appears to vary between vehicles.

¹This chapter is being prepared for submission to a peer-reviewed journal. The authors are Mark C. Anderson, Kent L. Gee, and Grant W. Hart. The interested reader is encouraged to find the published article once available.

A.1 Introduction

Rocket launches are occurring at a dramatically increasing rate around the world, with many new technologies developed since the early space race (Lubert, 2018). With many proven launch vehicles, and many more still in the design phase, it will become increasingly important to accurately predict the far-field noise caused by these launches. Such predictions are useful for environmental and community noise assessments, as the sounds can be heard up to tens of kilometers away from the launch site (Gee *et al.*, 2023; Kellison *et al.*, 2023).

There are two approaches to rocket noise modeling. The first is to use computational fluid dynamics (Bodony and Lele, 2008; Lyrintzis and Coderoni, 2020), but this is computationally expensive and can take a long time. The second, faster method is to use an acoustic field-based approach (Eldred, 1971; McInerny, 1996). The problem is that most acoustic-field rocket noise modeling techniques used today rely on methods and data from the 1960s and 1970s, primarily deriving from a single summary report known as NASA SP-8072 (Eldred, 1971). While the overarching methods are still valuable today, it has become clear that more data are needed to further improve the models (Lubert *et al.*, 2022). In the last fifty years, better sensors have become available and many improvements to measurement and analysis methods have come about. With the current increasing launch cadence, now is an opportune time to improve methods and add more data to improve future models.

The purpose of this chapter is to present methods for analyzing measured data collected during rocket launches to answer the following questions:

1. How much sound power is being produced?
2. What is the directivity?
3. How does the total sound power relate to the total mechanical power of the rocket, a quantity known as the acoustic efficiency?

We are not the first to ask these questions, nor the first to measure these quantities. For example, Cole *et al.* (1956, 1957) measured the sound power and directivity of aircraft and rockets almost seventy years ago. One limitation of the methods in Cole *et al.* (1956, 1957) is that the treatment of ground reflections for an airborne source is unclear. This leads to uncertainty in the final sound power calculations because they may or may not be contaminated by ground-reflection effects in the measured data. For sources flying high above the ground, the sound is indeed emitted into a free space (Cole *et al.*, 1956, 1957), but ground-based measurements will not measure free-space pressure. In this chapter, the effects of ground reflections are explicitly accounted for by removing them from the measured data, with the option to apply a frequency-dependent and angle-dependent ground-reflection model.

An additional shortcoming of the methods outlined in Cole *et al.* (1956, 1957) is that the vehicle trajectory is assumed to be linear. Although this may be a good approximation near the source, it is more accurate to have a method that accounts for the full three-dimensional trajectory. The methods outlined in this chapter use three-dimensional trajectories, which enables the methods to be used in

cases where the rocket begins to pitch over as it ascends. An improvement on the linear trajectory assumption was made by Mathews *et al.* (2021), but this was also limited by considering only a two-dimensional trajectory, which reduces the accuracy of measurements made outside the plane of flight.

The remainder of this chapter proceeds as follows. In Sec. A.2, the methods for calculating the source directivity from a three-dimensional launch trajectory are discussed and then the results are integrated to determine the overall sound power level (OAPWL) and acoustic efficiency. Details of two specific measurement campaigns as examples are given in Sec. A.3. The results from these analyses, along with comparisons to historical findings are shown in Sec. A.4, including improved estimates for the OAPWL for the Delta IV Heavy and Space Launch System (SLS) rockets. These comparisons lead to insights into what factors are most important for predicting rocket noise. Section A.5 contains the conclusions of the study. Also included are two chapter appendices that discuss (A) the removal of ground effects in these measurements and (B) the challenges that arise when trying to deduce the acoustic source properties using measurements that are too far away from the launch pad.

A.2 Methods

A.2.1 Directivity

The first step in calculating the source directivity is to establish the geometric relationships between the rocket, the dominant source region, and the measurement location. These relationships are illustrated in Fig. A.1. Importantly, the noise is not generated at the nozzle exits, but rather at some distance downstream from the nozzles, denoted as D_S . This distance refers to the maximum source region and is assumed to be 18 effective nozzle diameters ($d_{\text{eff}} = d\sqrt{N}$, where d is the diameter of a single nozzle and N is the number of nozzles) downstream (Gee *et al.*, 2013; Lubert *et al.*, 2022). For example, if the diameter of a single nozzle is $d = 1.4$ m and there are $N = 2$ nozzles, then the effective diameter is $d_{\text{eff}} = 1.98$ m. Although the true source region is not localized to a single point, it is assumed throughout this chapter that the measurements are far enough from the source that the point-source assumption is acceptable, with the closest measurement being $110 d_{\text{eff}}$ from the launch pad.

If the vehicle trajectory corresponds to the base of the vehicle, then the trajectory of the acoustic source can be found by

$$\vec{T}_S = \vec{T} - \hat{v}D_S, \quad (\text{A.1})$$

where $\vec{T}_S$ the vector pointing from the origin (generally chosen to be the launch pad) to the source, $\vec{T}$ is the vector pointing from the origin to the base of the rocket, and $\hat{v}$ is the unit vector pointed in the direction of the vehicle velocity. It is assumed that the rocket and the source location share a common velocity vector.

If $\vec{R}$ is the vector pointing from the source to the measurement location $\vec{P}$, then the observation angle θ can be solved for as

$$\theta(t_r) = \cos^{-1} \left(\frac{-\vec{V} \cdot \vec{R}}{|\vec{V}||\vec{R}|} \right), \quad (\text{A.2})$$

where $\vec{V}$ is the velocity of the vehicle and the source. Note that this is the angle as a function of the retarded time t_r and that the sound emitted at this trajectory point will take a finite amount of time to propagate to the receiver located at $\vec{P}$. Assuming straight-ray propagation and a constant sound speed, the sound corresponding to the angle θ can therefore be found at time

$$t = t_r + \frac{|\vec{R}(t_r)|}{c} \quad (\text{A.3})$$

in the recording, where c is the speed of sound (assumed to be 340 m/s throughout this chapter). Note that the trajectory data and the acoustic data must be aligned so that they begin at precisely the same moment. For example, if the vehicle lifts off at $t_r = 0$ seconds, then there should be a time delay of $|\vec{R}(0)|/c$ in the acoustic data before the sound corresponding to $t_r = 0$ arrives at the measurement location. Because some amount of noise is generally produced in the few seconds prior to the actual liftoff, care must be taken to ensure that the sound corresponding to $t_r = 0$ appears in the acoustic data at $t = |\vec{R}(0)|/c$.

An example of this mapping between observation angle θ and measurement time t is shown in Fig. A.2. At the beginning of the launch, the microphone (located approximately on the same plane as the launch pad) observes the source from a perpendicular angle. Because we have assumed the source location D_S is 18 d_{eff} below the base of the rocket, the source is initially underground, which is nonphysical because the true exhaust plume is deflected by the flame diverter. Thus, any observation angles corresponding to a below-ground source in Fig. A.2 are discarded before proceeding with further analysis. Additionally, as the vehicle continues upward and pitches over, some angles are observed twice. The redundant measurements later in the recording are also removed before further analysis.

With the observation angle θ mapped to the measurement time, levels and spectra can be calculated corresponding to each angle θ . These levels and spectra can then be mapped to points on a source sphere representing the rocket:

$$L(f, \theta) = L_{\text{meas.}}(f, \theta) - G(f, \theta) + 20 \log_{10} \left(\frac{|\vec{R}(\theta)|}{r_0} \right), \quad (\text{A.4})$$

where $L(f, \theta)$ are the levels on the source sphere (f representing the spectrum at each angle), $L_{\text{meas.}}(f, \theta)$ are the raw measured levels at the measurement location, $G(f, \theta)$ represents corrections for ground effects, and r_0 is the common distance to which the levels are corrected. For simplicity, it is assumed that $G(f, \theta) = 6$ dB (i.e., perfect pressure doubling at all frequencies). This is approximately true at the frequencies that dominate the sound power of rockets (Hart and Gee, 2023), though additional modeling efforts could improve the results at higher frequencies (Christian *et al.*, 2023; Gee *et al.*, 2014). Mathews and Gee (2025) show that values ranging from 5.8–6 dB can

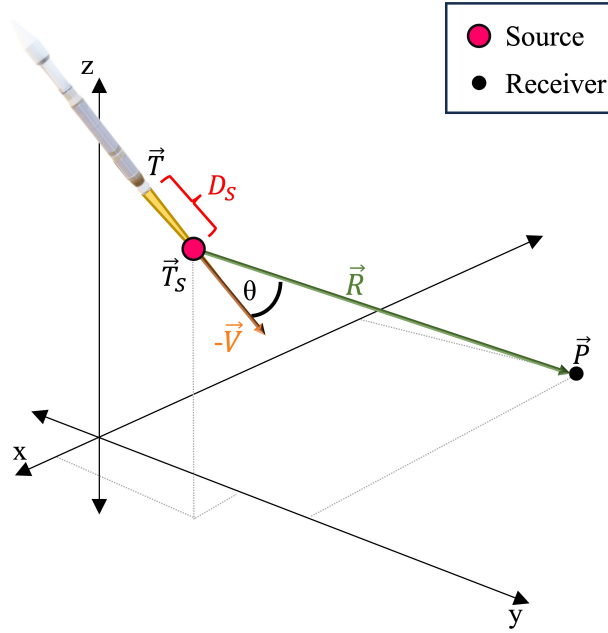


Figure A.1 Definitions of the various geometrical components relating the rocket, acoustic source location, and measurement location. $\vec{T}$ is the position of the base of the rocket. $\vec{T}_S$ is the position of the noise source region in the plume. D_S is the distance between the base of the rocket and the noise source region. $-\vec{V}$ is the negative of the vehicle velocity vector. $\vec{R}$ is the vector pointing from the noise source region to the microphone located at point $\vec{P}$. The gray dashed lines are included to illustrate the locations of $\vec{T}_S$ and $\vec{P}$ relative to the 3D coordinates. 3D model provided by NASA Visualization Technology Applications And Development (VTAD) (<https://science.nasa.gov/resource/atlas-v-401-3d-model>, Last Viewed: 04-13-2026).

be reasonable if the measurement is made on surfaces ranging from grass to concrete and the sonic boom research community has tended to use a reflection factor of 1.9–2.0, a value of 5.6–6.0 dB (Maglieri *et al.*, 2014; Lonzaga *et al.*, 2022). Nevertheless, for simplicity throughout this chapter, it is assumed that $G(f, \theta) = 6$ dB.

A.2.2 Sound Power

To determine the total sound power, the directivity information must be converted to intensity levels on the source sphere. The acoustic intensity is

$$\vec{I} = \frac{p_{\text{rms}}^2}{\rho_0 c}, \quad (\text{A.5})$$

where $\vec{I}$ is the intensity, p_{rms}^2 is the root-mean-square (rms) pressure, and ρ_0 is the ambient air density.

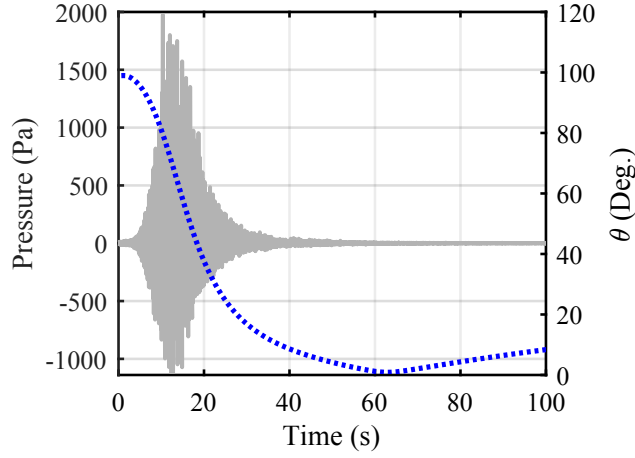


Figure A.2 The angle between the exhaust plume and the measurement location. The angle includes the time delay corresponding to the distance traveled to arrive at the microphone.

Once the intensity values are known at each angle, the sound power W in Watts is determined by the integral using $\vec{I}$ and the area vector $d\vec{S}$,

$$W = \oint_S \vec{I} \cdot d\vec{S}. \quad (\text{A.6})$$

Or, in the discrete approximation,

$$W = \sum_{n=1}^N |\vec{I}_n| \Delta S_n, \quad (\text{A.7})$$

where ΔS_n for an axisymmetric source sphere has been solved for by Matoza *et al.* (2013) using the results of Leishman *et al.* (2006),

$$\Delta S_n = 4\pi r_0^2 \sin^2 \left(\frac{\Delta \theta_n}{4} \right); \text{ For } n = 1, N \quad (\text{A.8})$$

$$\Delta S_n = 4\pi r_0^2 \sin(\theta_n) \sin \left(\frac{\Delta \theta_n}{2} \right); \text{ For } 2 \leq n \leq N - 1. \quad (\text{A.9})$$

Once the power is known, it is represented in decibels relative to 1 picowatt. This decibel quantity is referred to as the overall sound power level (OAPWL) throughout this chapter. The sound power level spectrum is referred to as the $\text{PWL}(f)$.

A.2.3 Sound Power Radiated in the Forward Direction

So far, these methods determine the radiation only in the aft direction, omitting any radiation in the forward direction. This results in a slight underestimate of the total sound power. Matoza *et al.* (2013) investigated this question for different supersonic jets and found that the radiation in

the forward direction tends to be small compared to the radiation in the aft direction. Figure A.3 explores this problem directly for rockets. The data come from Space Shuttle reusable solid rocket motor (RSRM) data from Gee *et al.* (2013) and corrected for source location in Lubert *et al.* (2022). The OASPL is shown as a function of the angle relative to the plume at 80 diameters from the source. If the full curve is integrated, the OAPWL is 198.5 dB. However, if only the portion of the directivity between 20–85° is integrated relative to the plume (a typical visible portion of the directivity from ground-based measurements during a vertical launch), then the OAPWL is estimated to be 197.5 dB. Thus, we conclude that omitting the radiation in the forward direction reduces the OAPWL estimate by approximately 1.0 dB. To account for this, we recommend adding 1.0 dB to all OAPWL estimates calculated from launch data where only the lower hemisphere of the directivity is measured.

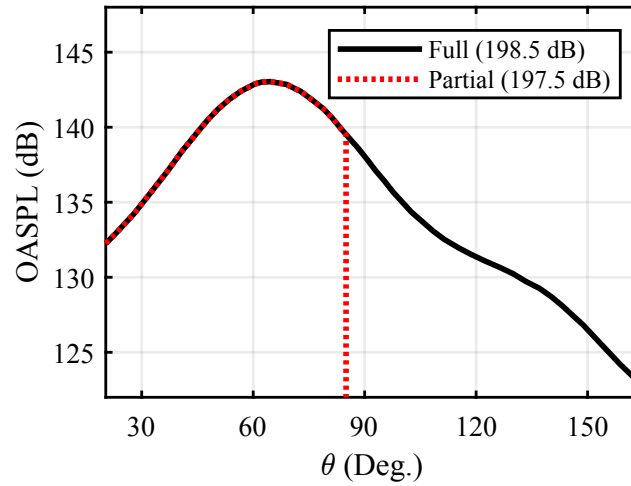


Figure A.3 The overall levels for the Space Shuttle RSRM at a distance of 80 diameters, digitized from Lubert *et al.* (2022) and interpolated here. The black line represents a full directivity from 20–180° and the red dashed line represents a directivity from 20–85°.

Once the sound power is calculated, the frequency-dependent directivity indices can be calculated as

$$Q(f, \theta) = L(f, \theta) - \text{PWL}(f) + 10 \log_{10}(4\pi r_0^2). \quad (\text{A.10})$$

The overall directivity indices can be similarly calculated by using the overall levels rather than the spectra,

$$Q(\theta) = L(\theta) - \text{OAPWL} + 10 \log_{10}(4\pi r_0^2). \quad (\text{A.11})$$

If the OAPWL and directivity indices are known, or can be estimated, then Eqs. A.10 and A.11 can be used to predict levels at different distances from the source by varying the parameter r_0 (Eldred, 1971; McInerny, 1992), though care must be taken to properly include ground-reflection effects in the final levels.

A.2.4 Acoustic Efficiency

The acoustic efficiency η is defined as the ratio of the radiated acoustic power to the total mechanical power of the rocket (Franken, 1958; Sutton and Biblarz, 2017),

$$\eta = \frac{W}{W_{\text{mech.}}} = \frac{W}{\frac{1}{2}TU_e}, \quad (\text{A.12})$$

where T is the total thrust and U_e is the mean velocity at the nozzle exit. Although exit parameters are preferable, using the fully-expanded values produces results accurate to within 0.3 dB (Mathews and Gee, 2025).

A.3 Measurements

These methods can be best illustrated by using an example. Acoustical measurements were made during the Landsat 9 and JPSS 2 missions originating from Vandenberg Space Force Base, CA. The vehicle used for both missions was the United Launch Alliance Atlas V rocket in its 401 configuration. The 401 designation indicates a four-meter fairing, zero solid rocket boosters, and a single engine on the second stage. For this analysis, the most relevant characteristic is the lack of solid rocket boosters, leaving only the single RD-180 engine (which has two separate nozzles) to power the initial phase of flight. A photograph taken during the JPSS 2 mission is shown on the left in Fig. A.4 and a schematic of the Atlas V rocket is shown on the right in Fig. A.4.

Detailed documentation of these measurement campaigns can be found in Cunningham *et al.* (2023) for the Landsat 9 launch and Mathews *et al.* (2023) for the JPSS 2 launch. For the purposes of this chapter, it is sufficient to say that measurements were made using ground-based inverted microphone setups (James *et al.*, 2020a; Anderson *et al.*, 2022a) at a variety of distances (ranging from 220 m to 13.6 km) and headings relative to the launch site. The microphones used were 6.35 mm (0.25 in) and 12.7 mm (0.5 in) GRAS microphones. Figure A.5 shows a map of the stations set up around VSBF for the two launches. Although there were also measurements made at farther distances, Fig. A.5 is cropped to better show the stations nearer to the launch pad that are used in this analysis. For this analysis, only measurement stations within 1 km of the launch pad are used, though results from the farther stations are considered in Chapter Appendix B to demonstrate some challenges associated with using the farther measurements.

The Landsat 9 mission launched around 11 AM local time on a cloudy day. The JPSS 2 mission launched around 3 AM local time in the middle of a clear night. Despite these differences in weather and time of day, the acoustic data are assumed to be similar between flights. To validate this claim, Fig. A.6 shows measured results from a consistent station located about 1.4 km from the launch pad for both missions. Subplot (a) shows the one-second equivalent levels and subplot (b) shows the one-third octave (OTO) band spectra over each recording's 6 dB-down period, which lasted approximately 30 seconds in both cases. The overall levels in (a) suggest that the total sound energy was consistent as a function of time between the two launches. The spectra in (b) suggest that the frequency content was similar during the highest-amplitude portions of the

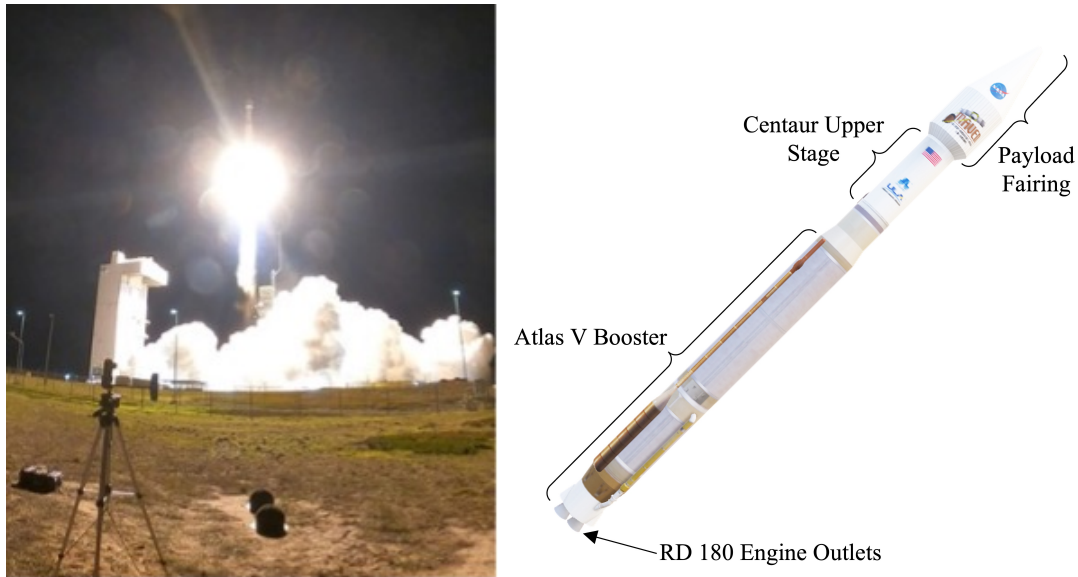


Figure A.4 (Left) The Atlas-V rocket lifting off from SLC-3W during the Landsat-9 mission. (Right) A schematic of the Atlas-V rocket in the 401 configuration used for both flights. 3D model provided by NASA Visualization Technology Applications And Development (VTAD) (<https://science.nasa.gov/resource/atlas-v-401-3d-model>, Last Viewed: 04-13-2026).

recordings. Interestingly, the JPSS 2 spectrum does show higher values by up to about 5 dB between 100–3,000 Hz. This difference may be induced by the cloud layer during the Landsat 9 mission, as opposed to the clear night during the JPSS 2 mission. Although meteorological effects on rocket noise propagation remains an important topic of future research, it is assumed throughout this chapter that the meteorological effects are small. Except where explicitly noted, all analyses in the remainder of this chapter will use measurements recorded within 1 km of the launch pad to reduce any longer-range propagation effects.

A.4 Results

A.4.1 Atlas V

The five measurements made within 1 km of the launch site were used to produce the directivities shown in Fig. A.7. In subplot (a), all five calculated directivities are shown in gray, and the average (using mean squared pressures) is shown in black. The average frequency-dependent directivity is shown in subplot (b). The peak frequency is around 40 Hz and the peak frequency is a function of the observation angle as expected.

Using the averaged directivity shown in Fig. A.7, and adding 1.0 dB to the final sound power to account for radiation in the forward direction, the total sound power level of the Atlas V rocket in

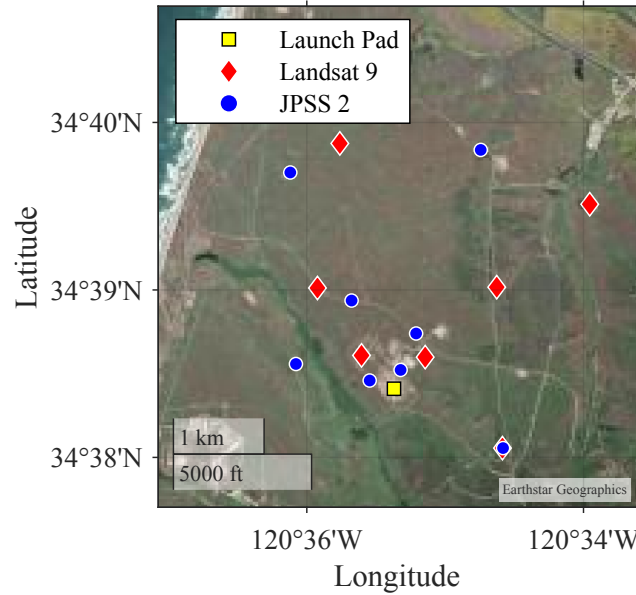


Figure A.5 A map showing the measurement locations and the launch site for both measurement campaigns.

the 401 configuration is 193.0 dB (re 1 pW), or 20.0 MW when using the averaged directivity. If the calculation is instead performed for each of the five individual measurements, then the range is from 192.2–193.9 dB (energy average of individual powers = 193.0 dB as well).

Using the frequency-dependent directivity, the same process can be followed for each frequency band, producing the sound power level spectra shown in Fig. A.8. The averaged sound power spectrum peaks at 40 Hz and has a 3 dB-down range from about 16–80 Hz. The nulls measured between 400–600 Hz at two of the stations have little impact on the averaged result. If a curve fit is performed over the 6 dB-down region of the directivity indices then the peak directivity index is 4.7 dB at 67°, with the full directivity indices shown in Fig A.9. This peak directivity index validates the use of 5 dB as a peak directivity index by Mathews and Gee (2025). To compare with the anticipated peak directivity angle, we use the convective Mach number definition defined by Gee *et al.* (2025), validated across jet exit Mach numbers from 1–11,

$$M_c = \sqrt{M_{ac}}, \quad (\text{A.13})$$

where M_{ac} is the acoustic Mach number defined by dividing the exit velocity by the ambient speed of sound. This convective Mach number definition was found to predict the peak radiation angle within about $\pm 5^\circ$ by Gee *et al.* (2025). With an exit velocity of 3,100 m/s (Hansen *et al.*, 2011; Harrison *et al.*, 2017; Wade, 2025), $M_{ac} = 9.12$ and $M_c = 3.02$. Applying the relation for the peak radiation direction

$$\theta_{\text{peak}} = \cos^{-1} \left(\frac{1}{M_c} \right), \quad (\text{A.14})$$

we get $\theta_{\text{peak}} = 70.7^\circ \pm 5^\circ$, which encompasses the observed value of about 67°.

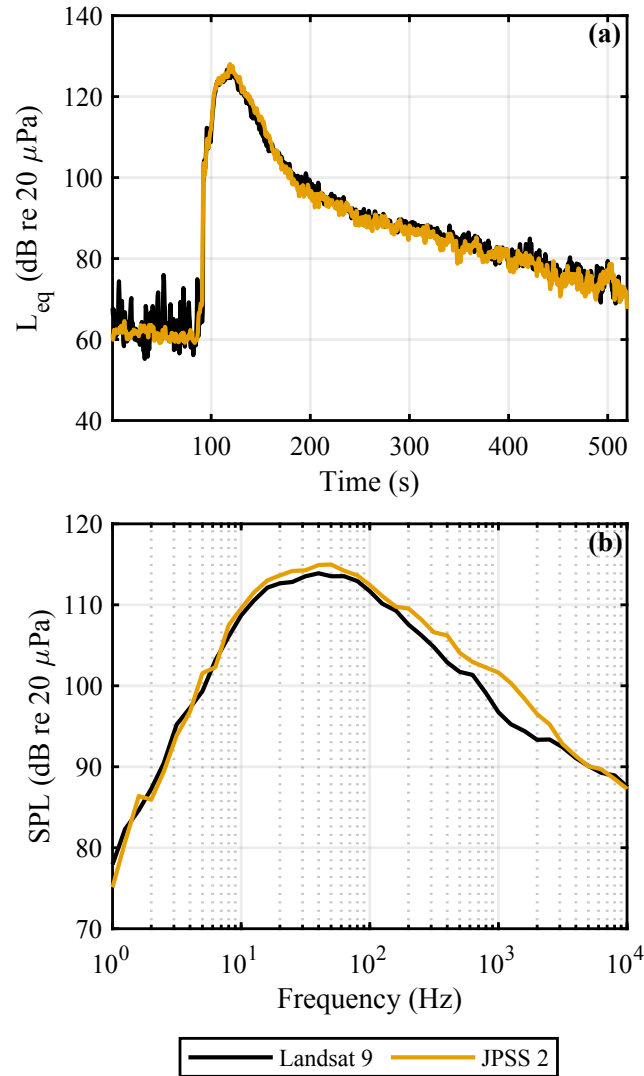


Figure A.6 (a) The running one-second overall level (L_{eq}) for both the Landsat 9 (black) and JPSS 2 (orange) measurements at a consistent location between flights. The measurement location was about 1.4 km from the launch pad. (b) The one-third octave band sound pressure level (SPL) spectra over the 6 dB-down periods of both recordings, which correspond to approximately 30 seconds for both cases.

With a total sound power of 20.0 MW, thrust of 3.8 MN (Hansen *et al.*, 2011), and exit velocity of 3,100 m/s the acoustic efficiency of the Atlas V 401 rocket is 0.34% when using the averaged directivity. If the calculation is instead performed for each individual measurement, then the range is from 0.28–0.42% (average also 0.34%), a sound power level difference of 1.8 dB. This suggests that when using a single measurement station within 1 km of the launch pad, a 2 dB uncertainty in the results can be anticipated.

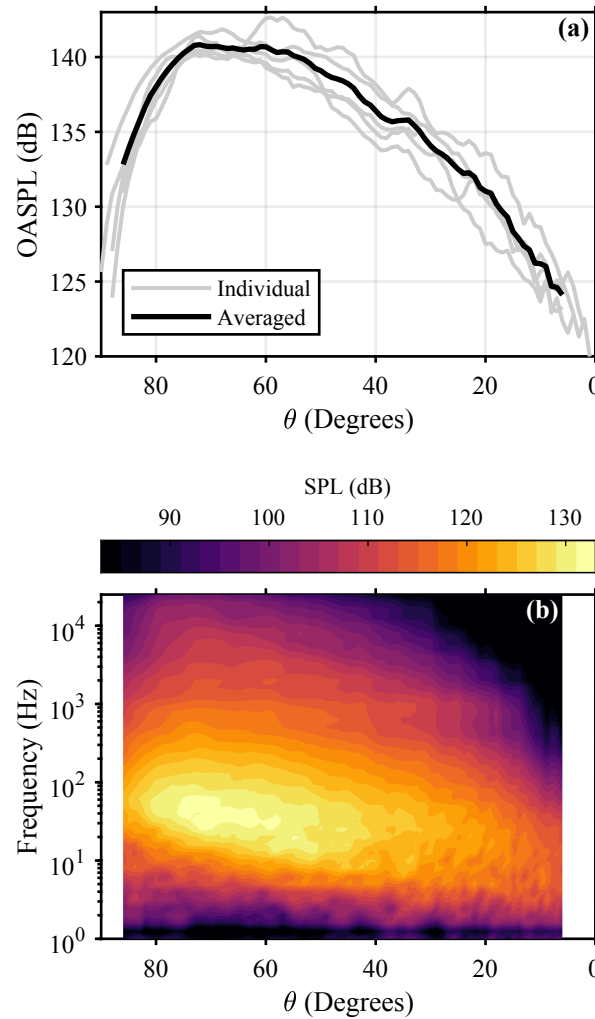


Figure A.7 The measured (a) overall and (b) frequency-dependent directivities at 100 d_{eff} .

A.4.2 Impacts on Prior Work

Previous analyses have not properly or explicitly accounted for ground reflections from airborne sources (Cole *et al.*, 1956, 1957; Franken, 1958; Mathews *et al.*, 2021; Hart *et al.*, 2022; Hart and Gee, 2023; Mathews *et al.*, 2023; Kellison and Gee, 2023). Cole *et al.* (1956, 1957) and Franken (1958) correctly state that a ground-based source will radiate into a half space, but do not consider ground reflection effects from airborne sources. Although a brief analysis on removing ground reflections is given by Cole *et al.* (1957), it is in the context of adjusting results in the frequency domain and does not appear to have been applied to the overall levels. Similarly, Hart *et al.* (2022) do not account for ground reflection effects in their results. Thus, their sound power of 197 dB for the Delta IV Heavy launch vehicle should be corrected to 192 dB, respectively (-6 dB for

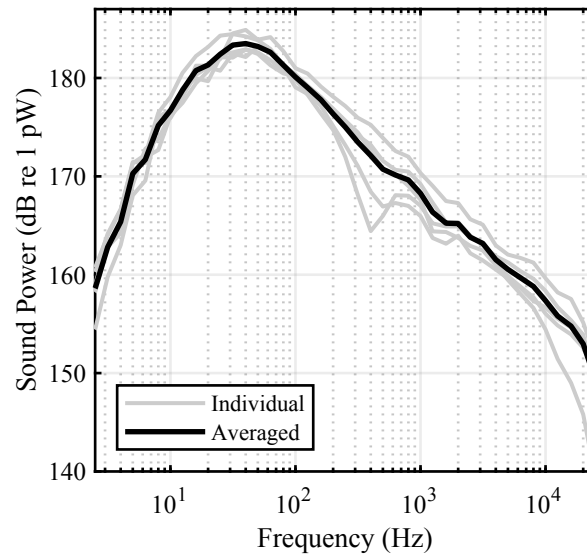


Figure A.8 The sound power level spectra for the Atlas V 401, calculated at each of the five stations within 1 km of the launch pad (gray) and the averaged (black), where the average was computed directly from the energy-averaged results in Fig. A.7(b).

ground reflections and +1 dB for forward-direction radiation). Meanwhile, Kellison and Gee (2023) attempted to remove ground-reflection effects from the Space Launch System (SLS) Artemis I launch but only removed 3 dB from the sound power under the assumption of half-space radiation. Thus, their estimate of 202.4 dB for the SLS sound power should be corrected to 200.4 dB (-3 dB more for ground reflections and +1 dB for forward-direction radiation). The updated SLS result in particular has interesting ramifications because it suggests that SLS may be substantially quieter than the Saturn V rocket, with a sound power of 204.7 dB (Kellison and Gee, 2023; Kramer, 1966). This, however, is not certain because the treatment of ground reflections in the original measurements by Kramer (1966) is not clearly stated.

Placing these updated results in the context of historical data provides valuable insights. In Fig. A.10, the OAPWL is plotted as a function of the rocket exhaust mechanical power. Dashed lines representing different acoustic efficiency values are shown. Included are historical results digitized from NASA SP-8072 (Eldred, 1971). The SP-8072 results alone might suggest that lower mechanical powers are correlated with lower acoustic efficiencies and vice versa, leading to a curve fit by Guest (1964) that has been used in modern rocket noise prediction software (James *et al.*, 2020b). However, the additional results included here do not support that trend. For example, the Delta IV Heavy appears to have an acoustic efficiency of less than 0.1%, despite it being among the more powerful rockets included. Additionally, SLS has an acoustic efficiency of about 0.2%, much less than the suggested value of 0.5% generally assumed for rockets (Guest, 1964; Lubert *et al.*, 2022). Note that the Falcon 9 results are not included here because there were other concerns with the method employed in Mathews *et al.* (2021), such as treating the trajectory and measurement as

being in the same plane and making measurements from too far away (see Chapter Appendix B). However, because historical treatment of ground reflections in rocket noise studies is unclear, the historical results shown in Fig. A.10 are not considered absolutely correct. Moving forward, we suggest that ground-reflection corrections be explicitly discussed when calculating the sound power and acoustic efficiency of rockets.

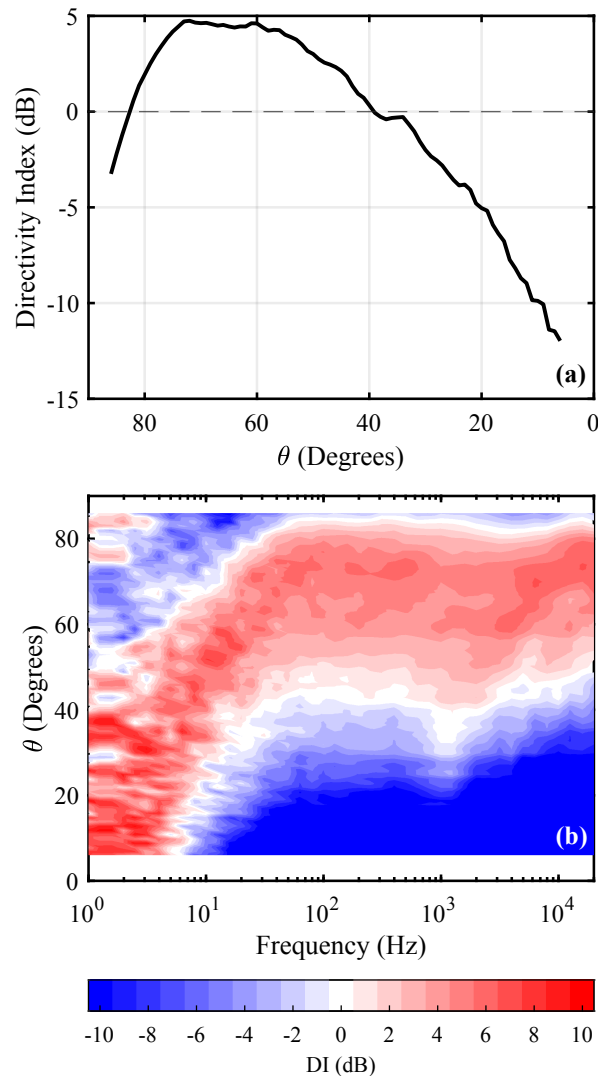


Figure A.9 The (a) overall directivity indices and (b) frequency-dependent directivity indices for the averaged directivity from the Atlas-V rocket launches.

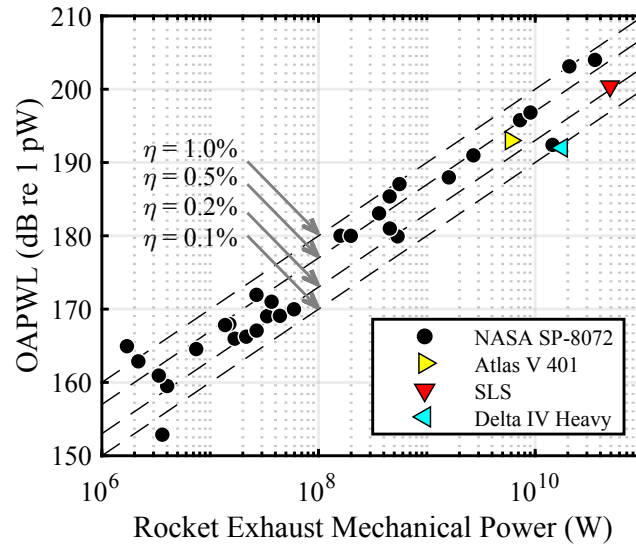


Figure A.10 Comparing the results in this chapter to those in the literature. (a) The OAPWL, normalized by exit diameter, as a function of exit velocity. (b) The OAPWL as a function of rocket exhaust mechanical power. Dashed lines of constant acoustic efficiency η are shown.

A.5 Conclusion

As a larger variety of rockets continue to launch at an increasing rate, it will become more important to have a physics-based understanding of rocket noise source characteristics. In this chapter, methods for educing source quantities from measured data were laid out. These methods have then been applied to two launch noise datasets collected during ULA Atlas V 401 rocket launches. Acoustic data were coupled with trajectory information to map out the noise directivity as a function of angle relative to the exhaust plume. Multiple directivity curves were averaged and then integrated to determine the overall sound power level of 193.0 dB (re 1 pW) with a corresponding acoustic efficiency of 0.34%.

Improvements have been made to previously published analyses to produce more accurate sound power levels. These two improvements are the proper removal of ground reflections, and the inclusion of sound power radiated in the forward direction. Those previous analyses did not remove ground reflection effects until after the sound powers were calculated and then did not remove them properly. Additionally, it was found that the radiation in the forward hemisphere should add about 1.0 dB to the total sound power. These effects have all been corrected and corresponding updated values are given for the Space Launch System (SLS) and Delta IV Heavy launch vehicles.

When the results for the Atlas V 401, SLS, and Delta IV Heavy are compared against historical literature, it becomes clear that historical scaling laws for rocket noise are insufficient to predict the OAPWL values for modern rockets. When considering the acoustic efficiency, values range from anywhere below 0.1% all the way up to about 1.0% (for historical results), a full order of magnitude.

The curve fit by Guest (1964) is not supported by these new results. We suggest that factors affecting the acoustic efficiency may include exhaust temperature and the clustering of multiple nozzles close to each other versus having more independent plumes.

More data are needed to further refine the simplified rocket noise source models. Measurements should be taken over a wide range of rockets, including smaller rockets with lower thrust, large rockets, and different types of propellant. Using such widespread data will assist in validating physics-based models for rocket noise.

Acknowledgements

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A.6 Chapter Appendix A: Ground Reflection Effects on Sound Power Estimates

Previous work by Cole *et al.* (1956, 1957) and Franken (1958) either do not accurately or explicitly treat ground reflection effects on the sound power. They do consider the fact that a ground-based source will radiate into a half space and that an airborne source will radiate into a free space, but do not accurately account for pressure doubling on the ground due to ground reflections from airborne sources. Similar limitations have been perpetuated in recent works on rocket noise source characterization, including the works by Hart and Gee (2023) and Kellison and Gee (2023), as discussed in Sec. A.4.2 above.

The safest and simplest approach to removing ground reflection effects on the analyses is to remove them from the measured pressure data, rather than waiting to remove them from the final directivity and sound power results. Assuming a rigid ground, the measured levels can have 6 dB subtracted from them to produce an effective free-field environment for source characterization and no further consideration need be given to the ground effects. Naturally, if the ground is not rigid then a more-complicated model can be applied to the measured levels to remove ground effects, including as a function of frequency. For example, the sonic boom community often assumes a ground reflection factor of 1.9–2.0 for the pressure (Maglieri *et al.*, 2014; Lonzaga *et al.*, 2022). All of this should be applied to the pressure data before calculating the directivity and sound power.

Attempting to correct for pressure-doubling at the ground after the sound power has been calculated can easily lead to confusion over whether 3 or 6 dB should be removed from the final sound power level. This confusion often stems from the fact that the noise source is radiating into a hemisphere above the ground (Cole *et al.*, 1956; Franken, 1958; Mathews *et al.*, 2023; Hart and Gee, 2023). This geometry can be modeled as a source-image pair as shown in Fig. A.11, where the plane between the sources has doubled pressures. It is tempting to say that one can remove the effect of ground reflections on the total sound power by simply dividing the calculated sound power in half, or by subtracting 3 dB.

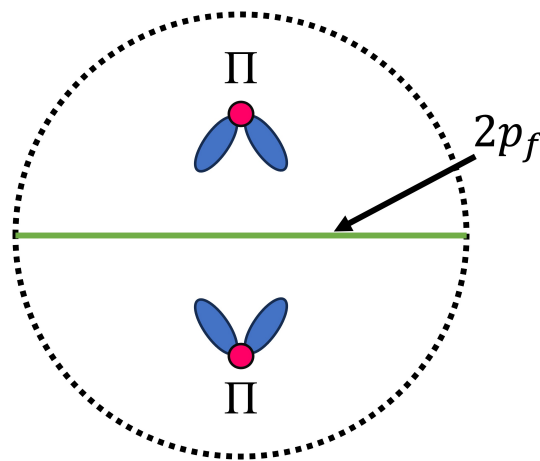


Figure A.11 An equivalent source-image pair that produces pressure-doubling along a plane between the sources. The red circles represent the acoustic sources, and the blue lobes represent source directionality. The green line indicates the location of the ground, and the dashed circle represents the sphere over which the intensity is calculated to determine the sound power.

Although this logic initially appears correct, there is an important issue. The geometry in Fig. A.11 is not the geometry from which the sound power is actually calculated. If the directivity curves were calculated at a single instant in time over an entire hemisphere encompassing the source, then it would be appropriate to integrate over that hemisphere to determine the sound power. Note, however, that the pressures would not be doubled everywhere on that hemisphere. Only on the ground are the pressures doubled. Even if this type of measurement were possible for a rocket in flight, the task of correcting for the ground reflections along the hemisphere would be complicated.

In reality, the directivity is traced out by a ground-based microphone as the rocket moves upward, producing a source directivity with doubled pressures at every angle. Although only the aft portion of the rocket directivity is measured, we can approximately account for radiation in the forward

direction as discussed in Sec. A.2.3. The fact that the pressures are doubled at every point along this source sphere is key to understanding why 6 dB should be subtracted from the total sound power. Consider the scenario in Fig. A.12(a), where the rocket has (somehow) been measured in completely-free space with no ground reflections. The pressures along the sphere are the true free-field pressures $p_f(\theta)$ corresponding to the free-field intensities $I_f(\theta)$. Integrating over this source sphere would accurately produce the total sound power Π of the source. Now consider Fig. A.12(b), which has doubled pressures $2p_f(\theta)$ everywhere along its surface. This is exactly what is obtained if the raw measured data are used to trace out the rocket directivity as the rocket moves relative to the microphone. In this case, the doubled pressures along the source sphere correspond to four times the free-field intensity according to Eq. (A.5). This quadrupling in the intensity along the source sphere corresponds to a power that is four times greater than the true source power. Therefore, to obtain the true sound power of a single source, 6 dB (a factor of 4 in power), must be subtracted from the final result.

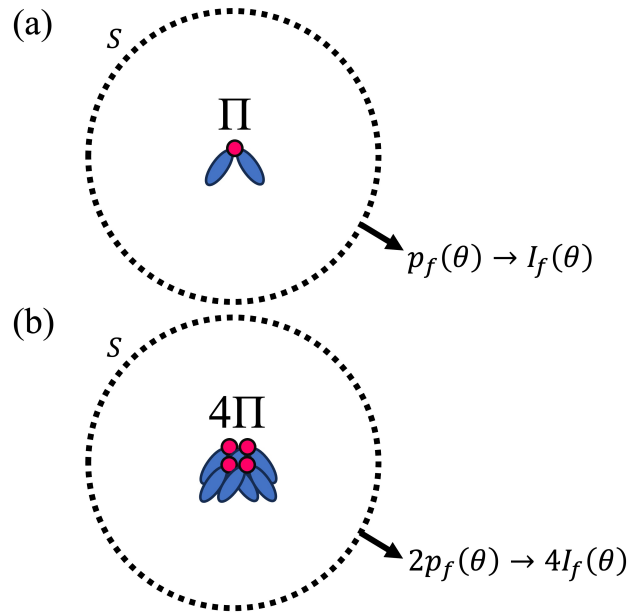


Figure A.12 (a) A sound source of power Π with directivity lobes indicated by the blue contours. This source is measured in free space and thus produces a free-field pressure and corresponding free-field intensity along a sphere encompassing the source. (b) Four identical sound sources, each of power Π , that produce twice the pressure everywhere on the sphere encompassing the sources relative to subplot (a).

Note that this complexity can be greatly reduced by removing the ground reflections from the measured data before the source directivity is calculated, as shown in Eq. (A.4). Another benefit of removing the ground effects from the measured data is that a more-complicated model can easily be applied (Christian *et al.*, 2023; Gee *et al.*, 2014). Such a model will be difficult to apply after the sound power has been calculated. Therefore, it is recommended that for all future measurements, the

measured sound levels be corrected to remove ground reflections before calculating the directivity and sound power. This is the approach that has been used for all results in this chapter.

It is worth highlighting an insightful study by Manhart *et al.* (1966) on an inverted nuclear rocket engine, which has a notably higher exhaust velocity compared to chemical rockets (Eldred, 1971). The exhaust was oriented toward the sky and directivity measurements were made along microphone towers. This geometry enabled them to calculate the sound power without pressure doubling from ground reflections. The final estimated acoustic efficiency was 0.2%, around half of the typically-assumed 0.5% and less than the estimated 0.34% for the Atlas-V rocket in the present chapter. As treatment of ground reflections is unclear in much of the historical data, it is possible that this study represents the best historical estimate of rocket acoustic efficiency. However, it is also possible that this estimated acoustic efficiency could be less than the estimates in Eldred (1971) and in this chapter because the measurements were made sufficiently far away that atmospheric absorption effects may have attenuated the sound power reaching the microphone array towers, noise propagated in the forward direction may not have been properly accounted for, or that the higher-speed exhaust has different acoustic properties (Manhart *et al.*, 1966; Eldred, 1971). Either way, the work of Manhart *et al.* (1966) should be investigated to gain further insight into the possible effects of ground reflections.

A.7 Chapter Appendix B: The Propagation Problem

In the Atlas V 401 analysis, the five stations closest to the launch pad (<1 km) were averaged to determine the final source characteristics. This was done to reduce noise in the final result while ensuring that the measurements were close enough to the source to have minimal propagation effects on the measured signals.

Figure A.13 highlights two aspects of what we call “The Propagation Problem”. Subplot (a) shows the OAPWL values calculated from all the stations deployed during both launches. The OAPWL values show a clear negative trend as distance from the launch pad increases. Because sound power is a source quantity, the measurement distance should not matter, as the integration surface grows with distance. Thus, sound energy is being dissipated during propagation from the source to the measurement locations. However, this is not a simple case of atmospheric absorption, as the frequencies which dominate the sound power are on the order of <50 Hz, which would imply minimal absorption over the distances considered. We suspect that the additional energy loss is due to nonlinear propagation effects, with shock formation transferring energy from the lower frequencies up to the higher frequencies (Petitjean *et al.*, 2006), where that energy is then rapidly absorbed. It is well known that acoustic nonlinearities are present in rocket noise (McInerny and Ölçmen, 2005; Baars *et al.*, 2014; Langenais *et al.*, 2019) and McInerny (1996) proposed that the nonlinear transfer of energy from low frequencies to high frequencies could explain a faster-than-expected decrease in OASPL with distance that also could not be explained with linear absorption.

Subplot (b) in Fig. A.13 shows the second part of “The Propagation Problem”, where it is observed that the peak frequency calculated over the 3 dB-down period of the launch noise decreases with measurement distance. There are a few possible explanations for this peak-frequency decrease

as a function of distance, and it is likely that multiple factors contribute to produce the total effect. One potential factor is that the vehicle is moving faster during the period of maximum level at the farther measurement stations, which could result in a Doppler effect that lowers the peak frequency, as stated by James *et al.* (2020b). Although the noise-generation mechanisms cast doubt on whether Doppler effects would be present (as the noise is generated by the mixing of two fluids rather than a point source (Ffowcs Williams, 1963; Nagamatsu *et al.*, 1969; Tam, 1972; Lubert *et al.*, 2022)), it is considered here for completeness. If the Doppler effect is relevant to this type of noise source, it would have the following impact on the frequency (Cole *et al.*, 1956)

$$\frac{f_{\text{new}}}{f_{\text{source}}} = \frac{1}{1 - \frac{|\vec{V}|}{c} \cos(180^\circ - \theta)}, \quad (\text{A.15})$$

where $|\vec{V}|$ is the rocket velocity and c is the speed of sound. In this expression, the 180° is included to account for the different definition of angle relative to the plume (θ) compared to Cole *et al.* (1956). When using the velocity magnitude and angle relative to the plume at the time that the peak levels are radiated from the source, the ratio $f_{\text{new}}/f_{\text{source}}$ at a distance of 220 m and 7200 m is 0.98 and 0.91 respectively. To fully account for the peak-frequency shift would require $f_{\text{new}}/f_{\text{source}} \approx 0.5$. Thus, if Doppler effects are present, they can account for only around 20% of the total shift in peak frequency. This is further evidence that the shift in peak frequency is not the result of Doppler effects.

Another potential explanation is that as the rocket gains altitude, the plume expands due to decreasing ambient atmospheric pressure. A wider plume could explain lower peak frequencies because the source region would be wider. However, this is unlikely to be a notable effect over the altitudes considered in this analysis, where peak directivity at the farthest stations occurred while the rocket was less than 4 km in altitude.

The final potential explanation briefly considered here is that nonlinear propagation effects lower the peak frequency. This explanation comes from the work of Gurbatov and Rudenko (2024). As the shock waves coalesce during propagation, the peak frequency tends to decrease. Although a notable decrease in peak frequency with propagation distance has not been noticed in military (Gee *et al.*, 2008) and laboratory jet research (Petitjean *et al.*, 2006), it is possible that the substantially-higher levels and farther distances associated with rocket-noise measurements could enable the effect to become noticeable, despite the lower frequencies involved in rocket noise. All of these possible explanations, along with any others, should be pursued in future research because measurement distance can have a noticeable impact on estimated source properties for rockets.

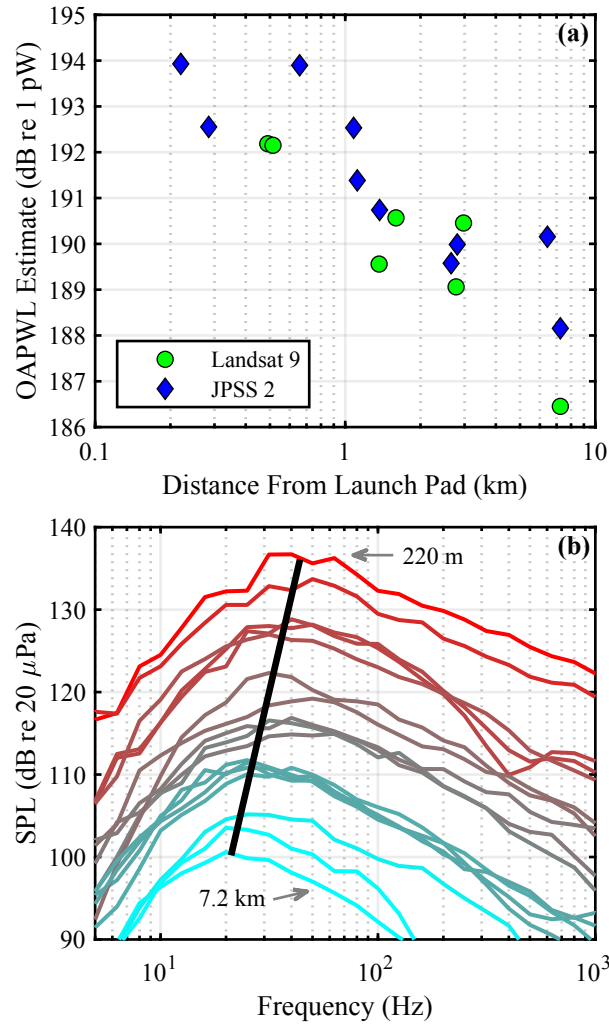


Figure A.13 Demonstration that the estimated (a) sound power and the measured (b) peak frequency during the period of maximum level both decrease as a function of measurement distance. The color in (b) corresponds to measurement distance (redder for closer and bluer for farther, correlating to the distances shown in (a)) and the black line indicates the trend in peak frequency.

Appendix B

Code Documentation

B.1 Introduction to COBRA

The COde for Sonic boom and Rocket Acoustics (COBRA) is research code written primarily by Mark Anderson for his research projects. COBRA contains many general-purpose signal processing functions along with various sonic boom, rocket, and nonlinear acoustics analysis and simulation capabilities. Although many of the core functions have specific unit tests callable via the “run_cobra_tests” script, it should not be assumed that the code is error-free. To the student who attempts to use COBRA, please verify that the code is capable of doing what you want and that the results make physical sense. Because COBRA is an evolving code repository designed around the specific use cases of Mark Anderson, it should never be used as a “black box”.

COBRA is designed around the philosophy that there should be as much commonality as possible in the codebase. For example, all spectral calculations ultimately get funneled through the same core functions for creating blocks, windowing, and scaling. Specific types of spectra are generally processed through functions that are ultimately wrappers for these core functions. Additionally, much of the COBRA code is written from an object-oriented perspective. The key idea behind COBRA’s object-oriented implementation is that it is convenient to store data and functions (called “methods”) together in a single unit. This enables rapid analysis and is one of the reasons why COBRA has been so useful throughout Mark Anderson’s research.

B.2 Tutorial

The following several pages contain a tutorial that should enable a new COBRA user to quickly become familiar with the most frequently-used code for sonic boom and rocket studies. While this is not an exhaustive tutorial of every COBRA capability, it can help with onboarding new students. The interested user is urged to look through the various functions available in the COBRA source code and see what other analyses can be performed. As always, users should create their own test cases to verify the code runs as expected and works for their purpose before trusting the code with their important analyses. This tutorial was last run in April 2026.

Sonic Boom and Rocket Analysis in COBRA

The **CO**de for sonic **B**oom and **R**ocket **A**coustics (COBRA) is designed to make sonic boom and rocket analysis easier and more efficient. This tutorial will walk you through a suite of functions that may prove useful to you. It is important to note that this code was developed primarily by Mark Anderson and is tailored to his specific research needs. There is no guarantee that it will work for other use cases. If you'd like to proceed to learn how to use COBRA, this guide should help introduce you.

COBRA comes with some sample data. Let's load that in as a **Signal** object:

```
sig = loadSampleData();
```

The **Signal** object can be thought of as a type of variable that also stores handy functions with it. We could have called our object anything we want. For example,

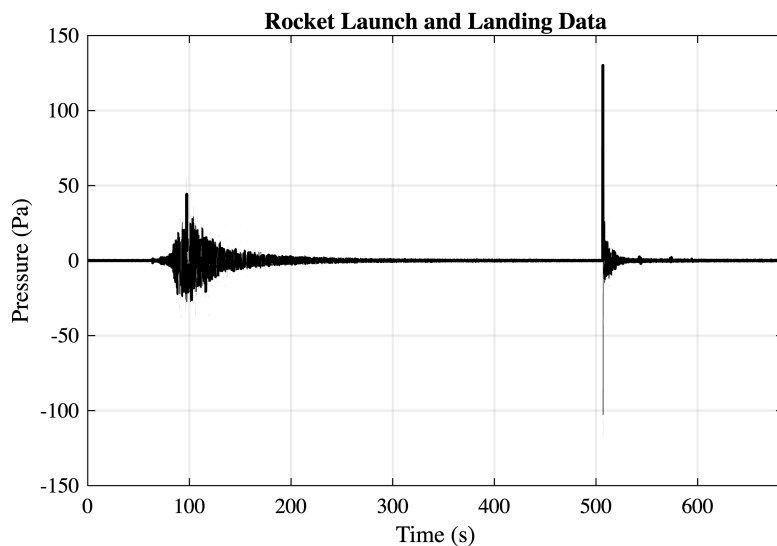
```
kent = loadSampleData();
```

creates an identical object. We'll proceed with **sig**. Let's make sure it has a name:

```
sig.Name = "Rocket Launch and Landing Data";
```

One of the useful functions available in **Signal** objects is the **plot** command:

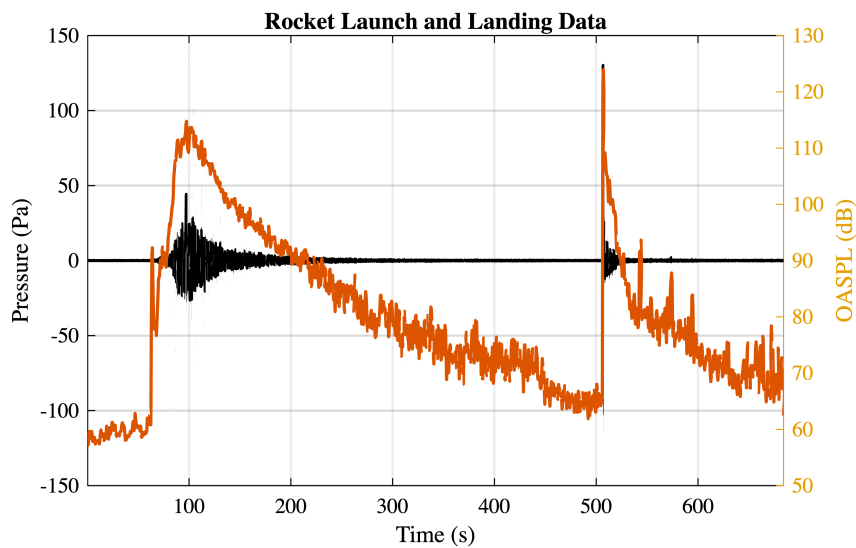
```
plotStyle('StandardStyle','COBRA') % Optional, just loading a favorite  
plotting style.  
sig.plot()
```



Initial Rocket Analyses

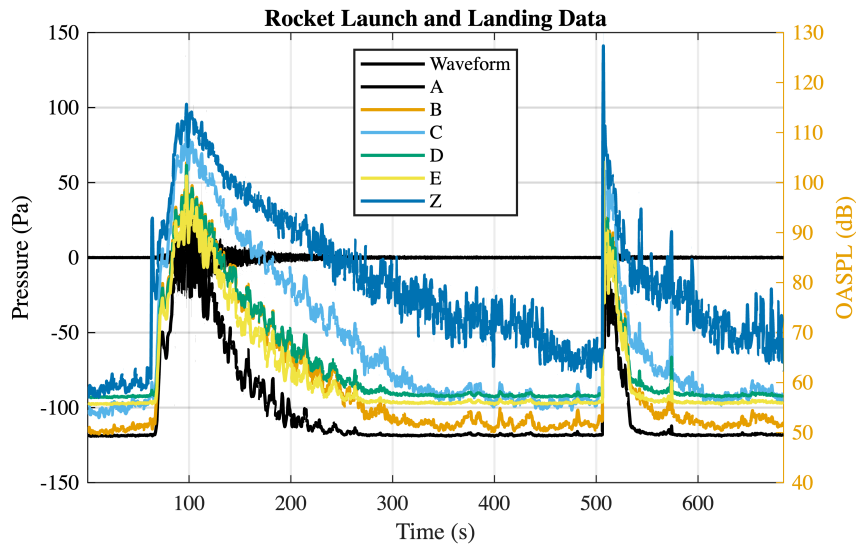
One of the analyses performed on rocket launch data is to determine the running level, often referred to as the 1-second Leq or 1-second running OASPL. That analysis can be easily performed using **Signal** objects:

```
figure()
sig.plotWaveformWithLevel()
```



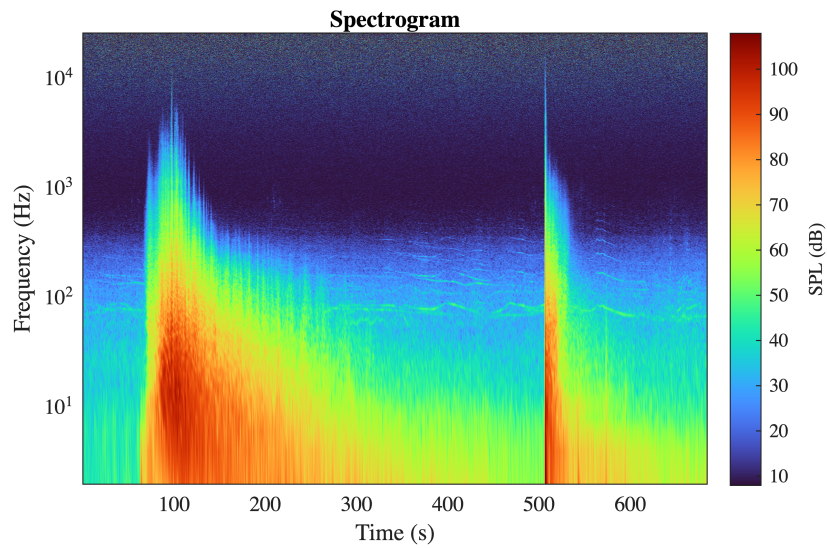
What if you want to show all of the different weighted levels? We can do that too. This calculation takes substantially longer because a spectrum must be calculated at each point. The resulting plot may not be the prettiest, but it is a useful analysis because weighted levels are often desired. All of this functionality can be more fully accessed in the **getOASPL** function in COBRA, whereas the **plotWaveformWithLevel** function within the **Signal** object is simply a quick way to access it.

```
figure()
sig.plotWaveformWithLevel('Weights',true)
legend('Location','north')
```



Speaking of spectra, another common analysis is to create a spectrogram over the entire launch. That can be done as so:

```
figure()
spectrogram_cobra(sig.Waveform,sig.SampleRate,'ShowPlot',true);
```

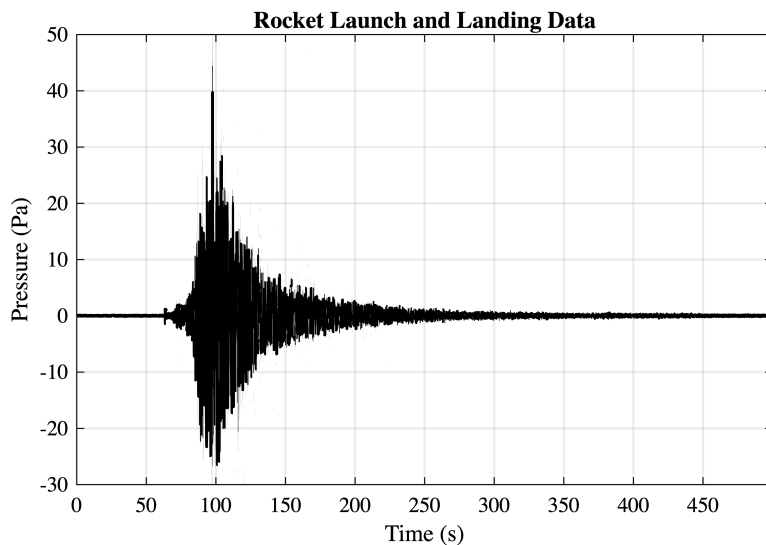


Spectra Over Max Period

Another common analysis is to take the highest-amplitude part of the recording and calculate the spectrum over that time period. For this case, be careful because the sonic boom is actually the highest-amplitude event, but we want to hone in on just the rocket noise. Therefore, we must trim the sonic boom off before continuing.

```
sig.Waveform = sig.Waveform(1:500*sig.SampleRate); % Only keep the first  
500 seconds
```

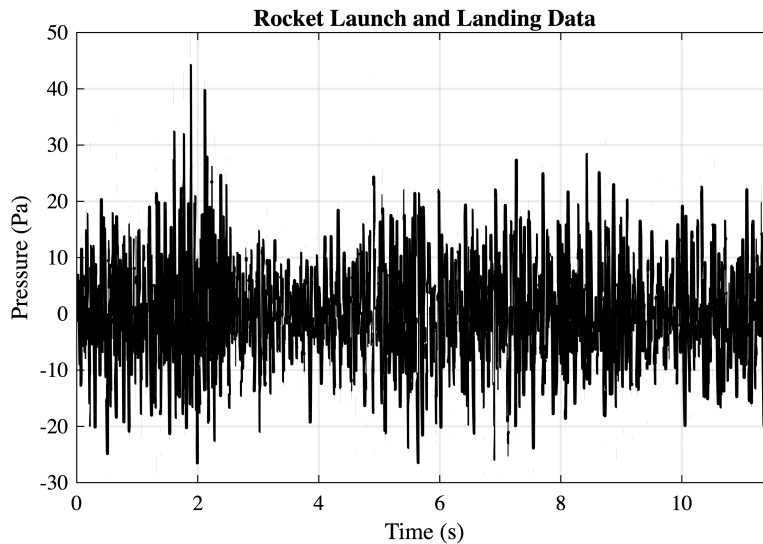
```
figure()  
sig.plot()
```



The function to further trim the waveform to just the highest-amplitude portion is called **trim2dBLimit**. If you want to trim to just to the 3 dB-down region, then you type

```
sig.Waveform = trim2dBLimit(sig.Waveform,sig.SampleRate,3);
```

```
figure()  
sig.plot()
```



You can see clearly that the waveform has been trimmed now to just the highest-amplitude part of the launch noise. What if we want to make a spectrum of this? I recommend knowing a few different functions and one object, namely the **Spectrum** object, which works similarly to the **Signal** object, but for spectra. The functions I would recommend knowing are:

- `getPxx()` - this is equivalent to `autospec()`, but with some additional features that make it more versatile.
- `fractionalOctave()` - this is copy-pasted from Dr. Gee's `FractionalOctave()` function.
- `pressure2dB()` - this takes pressure values and converts them into decibel values.

As always, more information about the inputs and outputs of each of these functions can be found in the comments at the top of each function. These comments can be accessed by typing "help X", "open X", or "doc X" in the MATLAB command window, where X is the name of the function you need help with.

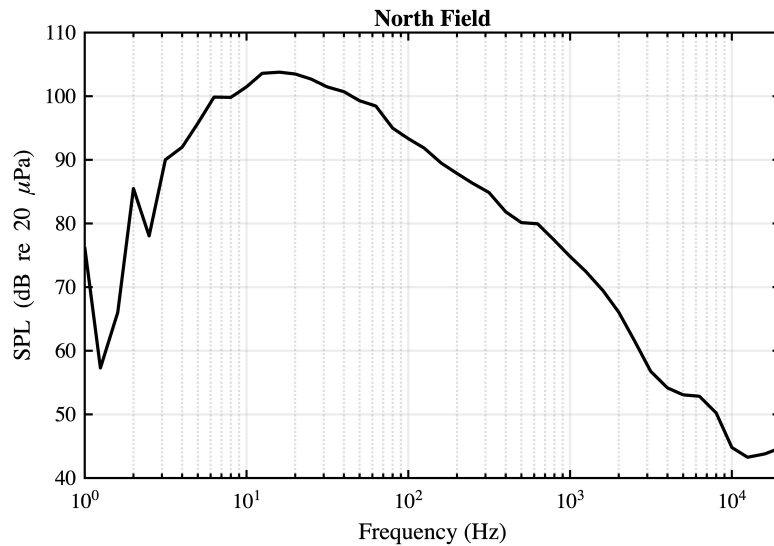
```
% Get the narrowband spectral density
[Pxx, f] = getPxx(sig.Waveform,sig.SampleRate);

% Convert the narrowband spectrum into one-third octaves
[spec, fc] = fractionalOctave(f,Pxx,[1,20e3],3);

% Turn the spectrum into decibel values
spec = pressure2dB(spec,'IsSquared',true); % Pxx and spec are both already
in units of squared pressure. That changes the decibel calculation

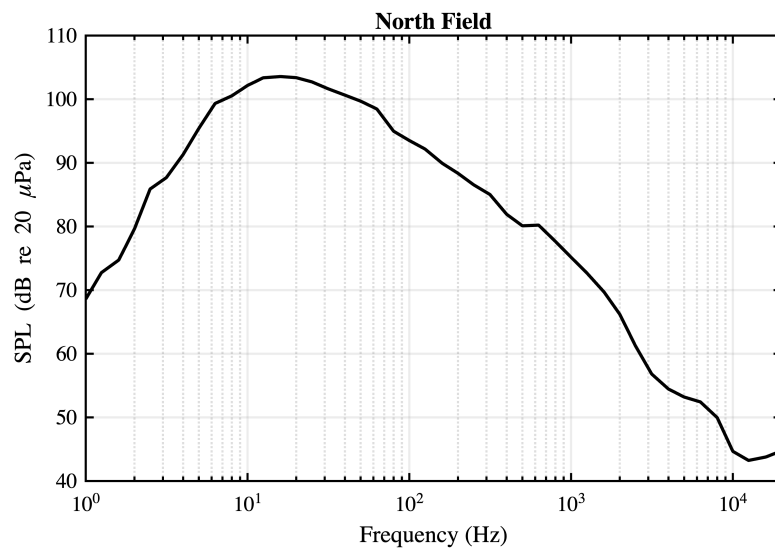
% Make a spectrum object for easy storage and plotting
% A spectrum object is similar to a signal object, but for spectra
NorthField_maxspec = Spectrum(fc,spec);
NorthField_maxspec.Name = "North Field";
NorthField_maxspec.Units = "SPL (dB re 20 \muPa)";
```

```
NorthField_maxspec.plot()
```



Notice those weird wiggles at low frequencies. That results from using a block size that is too small. Let's fix that by adjusting the block size.

```
[Pxx, f] = getPxx(sig.Waveform, sig.SampleRate, 'BlockSize', sig.SampleRate *  
3);  
  
[spec, fc] = fractionalOctave(f, Pxx, [1, 20e3], 3);  
  
spec = pressure2dB(spec, 'IsSquared', true);  
  
% Swap out the old spectrum for the new spectrum  
NorthField_maxspec.Values = spec;  
NorthField_maxspec.plot()
```



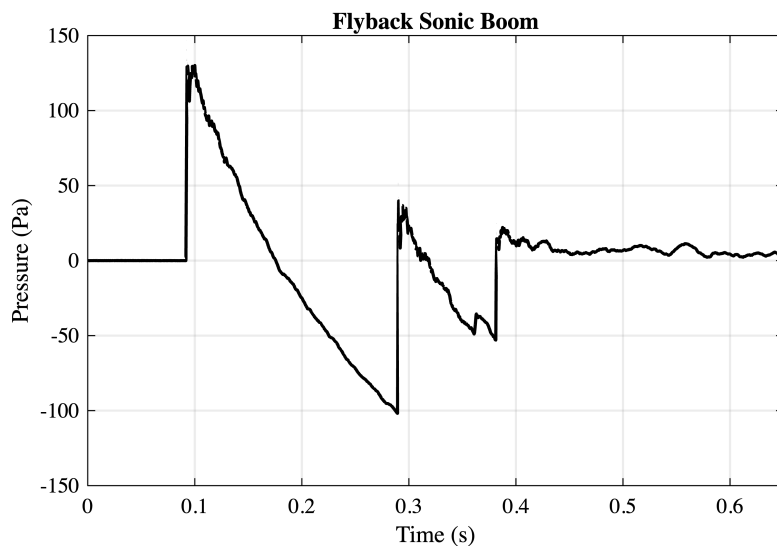
As an exercise, see if you can now plot the narrowband spectrum in decibels. Use any plotting method you'd like. Keep in mind that **Pxx** is already a squared quantity.

Initial Sonic Boom Analyses

We now turn our attention to the sonic boom portion of this sample recording. Let's trim the waveform to be over the landing period only.

```
boom = loadSampleData('boom');
boom.Name = "Flyback Sonic Boom";

figure()
boom.plot()
```



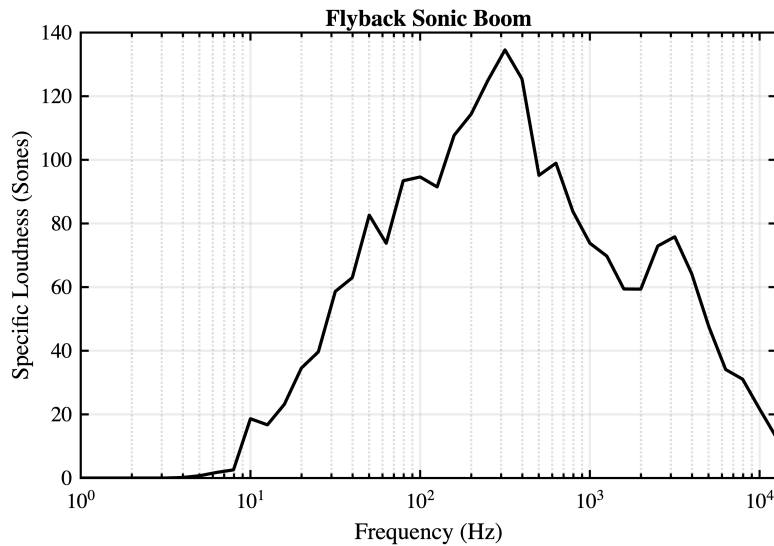
Sonic booms are considered "transient" events, whereas the launch noise is considerably more "stationary", meaning that the launch noise doesn't change too much from second to second (it does over several seconds, but relatively slowly). We use different methods for transient events. For example, the notion of OASPL is reserved for stationary noise, but we do have our own set of metrics used for sonic booms. These can be calculated as:

```
metrics = boom.getMetrics('MetricType','SonicBoom')
```

```
metrics = struct with fields:
    ASEL: 98.7783
    BSEL: 105.3874
    CSEL: 112.6941
    DSEL: 105.6811
    ESEL: 103.9082
    ZSEL: 123.9206
    Pmax: 130.0647
    PL: 114.7551
    Loudness: [1x1 Spectrum]
    ISBAP: 120.6011
    RiseTime: 4.5946e-04
```

Notice that one of the outputs is actually a spectrum. This loudness spectrum is returned from the Perceived Level (PL) calculation and attempts to give an estimate of which frequencies are the loudest for a human observer. We can plot it:

```
figure()
metrics.Loudness.plot()
```



Sonic Boom Spectra

A transient signal must be treated differently than a continuous noise signal. For example, the **getPxx** function breaks the signal into blocks and then averages the spectra from each block. This works for a stationary signal because, ideally, all of the blocks should produce the same spectrum and the averaging only reduces noise. However, that is an awful idea for a transient signal because its properties change dramatically. Therefore, we need to perform a single Fourier Transform over the entire recording. This is done via the **getTransientPxx** function. Note also that sonic booms should be given an exposure scaling. That is because the sonic boom metrics and spectra are exposure-based, meaning that they actually get larger and larger as more of the signal is added. This is taken care of in the **getMetrics** example shown above.

```
[Pxx, f] =
getTransientPxx(boom.Waveform, boom.SampleRate, 'Output', 'Exposure');

[spec, fc] = fractionalOctave(f, Pxx, [0.3, 20e3], 3);

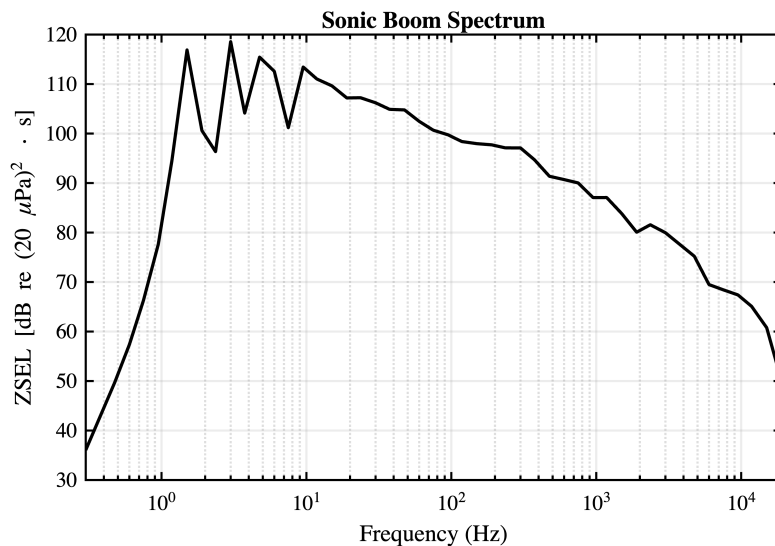
spec = pressure2dB(spec, 'IsSquared', true);

% Create a spectrum object
boom_spec = Spectrum(fc, spec);
boom_spec.Name = "Sonic Boom Spectrum";
```



```
boom_spec.Units = "ZSEL [dB re (20 \muPa)^2 \cdot s]";

figure()
boom_spec.plot()
```



We again see those funny spikes at the low frequencies. Since we can't increase our recording length without also changing our metric values, we add zeros to the recording. This is mathematically equivalent to increasing the recording length but contributes nothing to the metric values. This only works for exposure-type metrics.

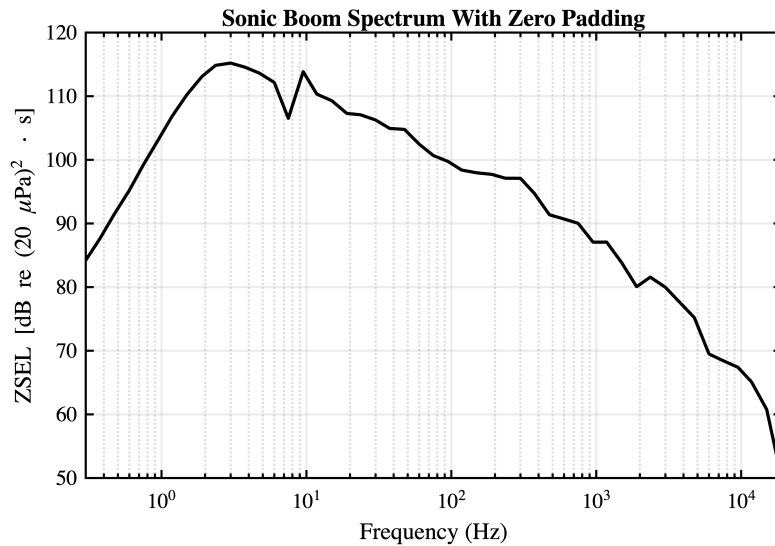
```
[Pxx, f] =
getTransientPxx(boom.Waveform, boom.SampleRate, 'Output', 'Exposure', ...
                'ZeroPad', boom.SampleRate*10);

[spec, fc] = fractionalOctave(f, Pxx, [0.3, 20e3], 3);

spec = pressure2dB(spec, 'IsSquared', true);

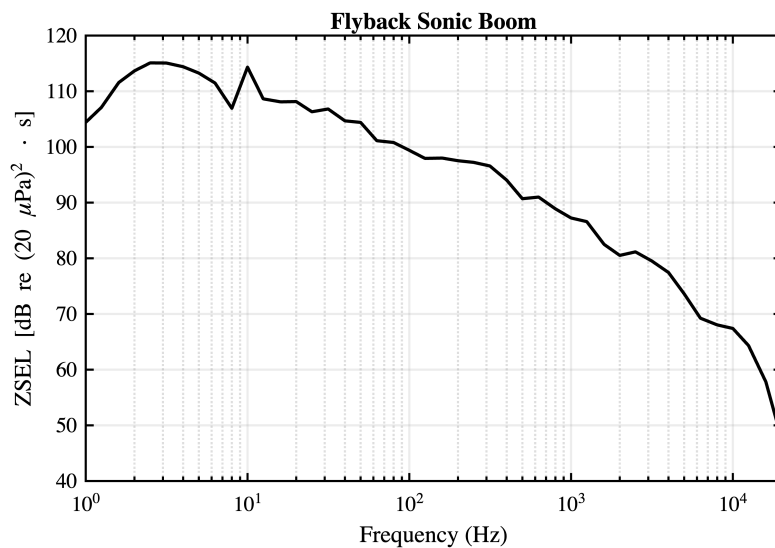
% Create a spectrum object
boom_spec = Spectrum(fc, spec);
boom_spec.Name = "Sonic Boom Spectrum With Zero Padding";
boom_spec.Units = "ZSEL [dB re (20 \muPa)^2 \cdot s]";

figure()
boom_spec.plot()
```



That's much better. Notice how many lines of code were needed for this spectrum. Because we make sonic boom spectra so often, and have created some standard practices for ourselves, you can actually plug a **Signal** object directly into a nice little function:

```
boom_spec = getSonicBoomSpec(boom);
figure()
boom_spec.plot()
```



Rocket Sound Power

We now move to a different part of the COBRA code, the rocket directivity calculations. Our first step is to load in the trajectory data. The data need to be loaded into a **Trajectory** object. There are a number of ways that you can import the trajectory data. My favorite is to get MATLAB to automatically create a function for me, which I've included in COBRA as `import_saocom()`, named after the mission.

```
clear; close all;

traj = import_saocom('SAOCOM-1A_Stage-1-FlightClubIO.csv'); % Data were
downloaded from flightclub.io
traj.interpolate(1.0); % Interpolates the trajectory onto a desired time
scale

sig = loadSampleData();

% Trimming the launch noise recording to start at the same moment that the
% rocket lifts off.
distance = 8291;
delay = distance/340; % Time for IOP to travel from launch pad to microphone
start_time = 63.3; % IOP begins
start_time = start_time + 3; % delay between IOP and launch
sig.Waveform = sig.Waveform(floor((start_time - delay) *
sig.SampleRate):end);

sig.Waveform = sig.Waveform(1:300*sig.SampleRate); % Only the first 300
seconds (to avoid the boom)
```

Note that the **Trajectory** object has a `plot()` command, just like **Signal** and **Spectrum** objects do. Now we need to turn our recording into a **Microphone** object. The **Microphone** object is special because it contains information about the measurement location. One of the properties of the **Microphone** object is actually a **Signal** object, so perhaps you could think of a **Microphone** as a generalization of a **Signal** that also includes precise information about where the recording was made.

```
mic = Microphone;
mic.Signal = sig;
mic.Signal.Name = "SAOCOM 1A North Field";
mic.Name = mic.Signal.Name;
mic.Position = [6434, 5230, 9]; % Approximate location (meters) relative to
the launch pad.

% North = positive Y
% East = positive X
% Up = positive Z
```

Now we are ready to use the `getLaunchDirectivity()` function. This function returns a **Directivity** object that can then be used to easily produce results.

```
WindowTime = 5; % Five seconds per analysis window
```

```

BlockSize = mic.Signal.SampleRate*5; % Changes the frequency resolution
Deff = 0.92*sqrt(9); % Effective nozzle diameter
ScaledDistance = Deff*100; % 100 effective exit diameters for the Falcon 9
(meters)

Dir = getLaunchDirectivity(traj,mic,...
    'WindowTime',WindowTime,...
    'BlockSize',BlockSize,...
    'ScaledDistance',ScaledDistance, ...
    'GetPower',true, ...
    'AutomaticTrimming',true, ...
    'MARP',18*Deff);

```

Getting Launch Directivity for SA0COM 1A North Field

And just like that, we have created the directivity. Let's have some fun now with the results.

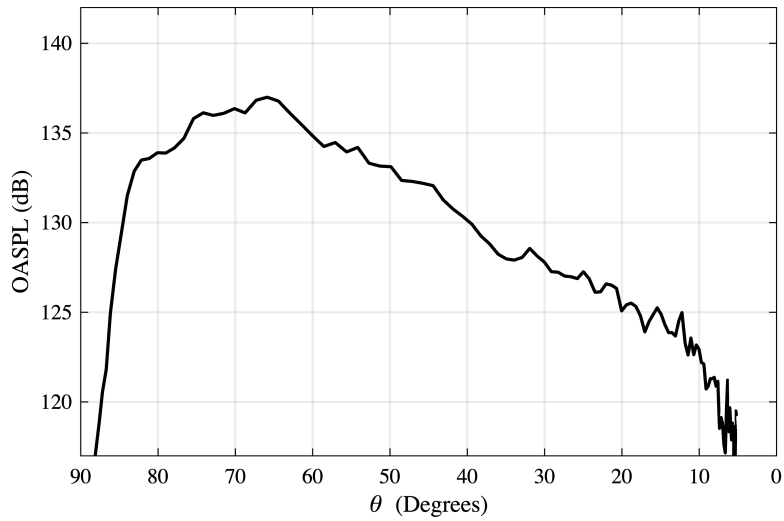
Dir

```

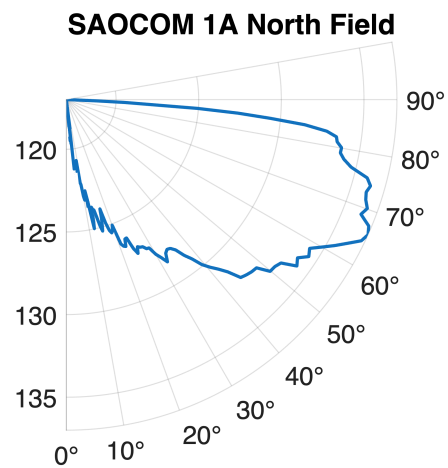
Dir =
  Directivity with properties:
      Name: "SA0COM 1A North Field"
      RocketTime: [118×1 double]
      MicrophoneTime: [118×1 double]
      TrueDistances: [118×1 double]
      TiltAngle: []
      Theta: [118×1 double]
      Phi: []
      RocketVelocity: [118×1 double]
      OASPL: [118×1 double]
      OASPL_Measured: [118×1 double]
      Spectra: [1×1 struct]
      ScaledDistance: 276
      Power: 190.8700
      PowerSpectrum: [1×1 Spectrum]

```

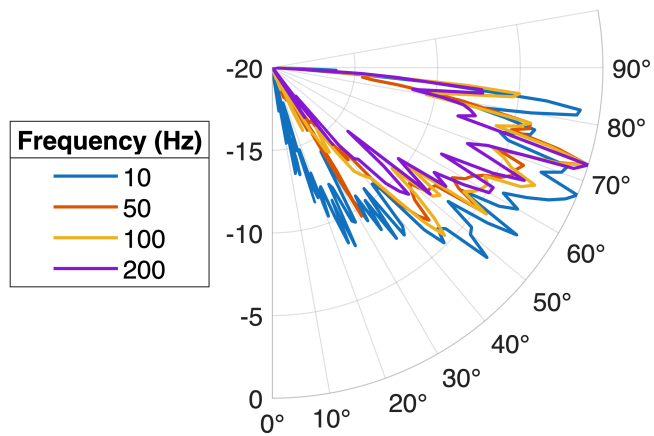
Dir.OASPL_vs_Theta()



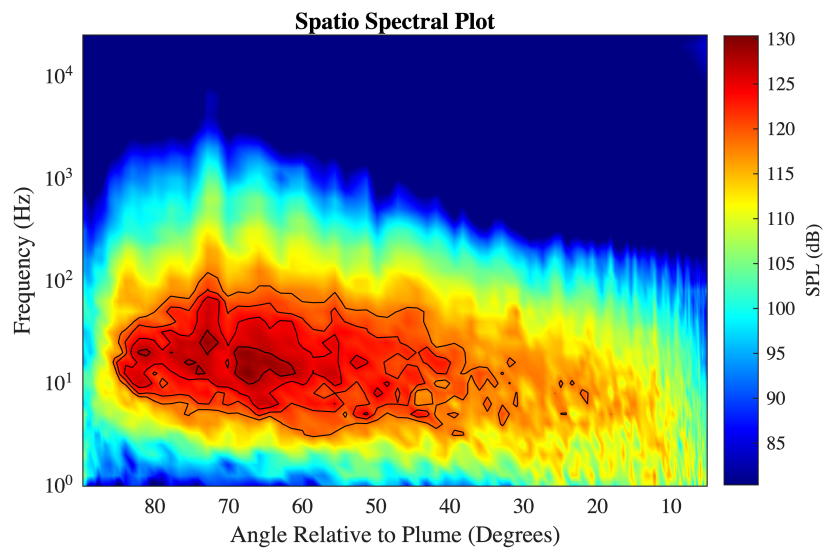
```
Dir.OASPL_vs_Theta('Style','polar')
```



```
figure()
Dir.FrequencyDirectivity()
```



```
figure()
Dir.SpatioSpec()
```



We can also access all of the OTO band spectra:

```
Dir.Spectra
```

```
ans = struct with fields:
```

```

Narrowband: []
OT0: [118x45 double]
OT0Frequencies: [1 1.2500 1.6000 2 2.5000 3.1500 4 5 6.3000 8 10 12.5000 16.0000 20 25 31.5000 40 50 63 80 100 125 160]

```

As usual, see the comments at the top of `getLaunchDirectivity()` for more details.

Notice the many useful output variables. Here's a rundown:

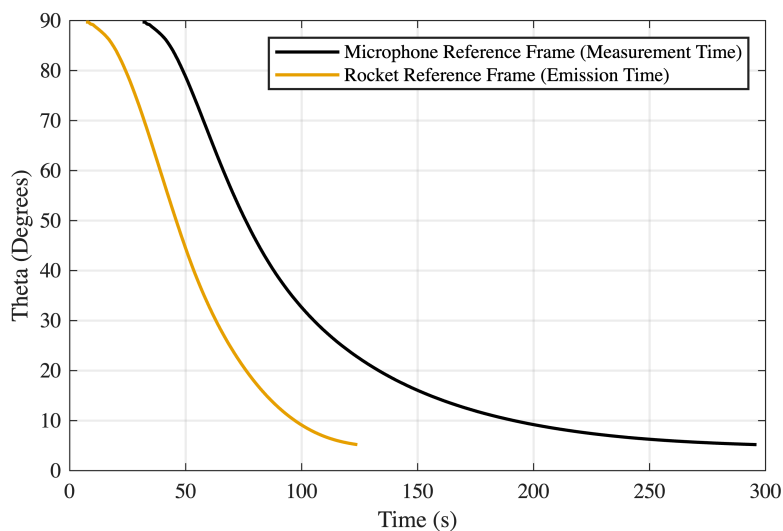
- `RocketTime` = the time in the rocket's reference frame
- `MicrophoneTime` = the time in the microphone's reference frame
- `TrueDistances` = the actual distance between the microphone and the rocket
- `TiltAngle` = the tilt of the rocket
- `Theta` = the angle of the rocket plume relative to the microphone
- `OASPL` = the OASPL as a function of time. You get one OASPL value corresponding to each trajectory point.
- `Power` = the total sound power (dB).

Of course, you can also make plots of any combination you want. For example, how does the angle vary in the rocket's reference frame versus the microphone's reference frame?

```

figure()
plot(Dir.MicrophoneTime,Dir.Theta); hold on
plot(Dir.RocketTime,Dir.Theta)
grid on;
box on;
xlabel("Time (s)");
ylabel("Theta (Degrees)");
legend('Microphone Reference Frame (Measurement Time)', ...
       'Rocket Reference Frame (Emission Time)', ...
       'Location', 'NorthEast')

```



Notice how the angle evolves faster in the rocket's reference frame, but it takes a while for the sound emitted at each angle to reach the microphone. The farther away the rocket is, the longer it takes for the sound to travel.

B.3 Comparison with Legacy Code

The core signal processing functions in COBRA have also been directly tested against older, legacy functions. Although several such comparisons are made as part of the unit tests available in the “run_cobra_tests” script, it is useful to demonstrate here as well that the COBRA and legacy functions produce the same results. In part, this serves as a concrete benchmark that as of this dissertation work, the COBRA and legacy codes agree. The comparisons are made over the next several pages. These comparisons were last run in April 2026.

getPxy() vs. crossspec()

```

clear;

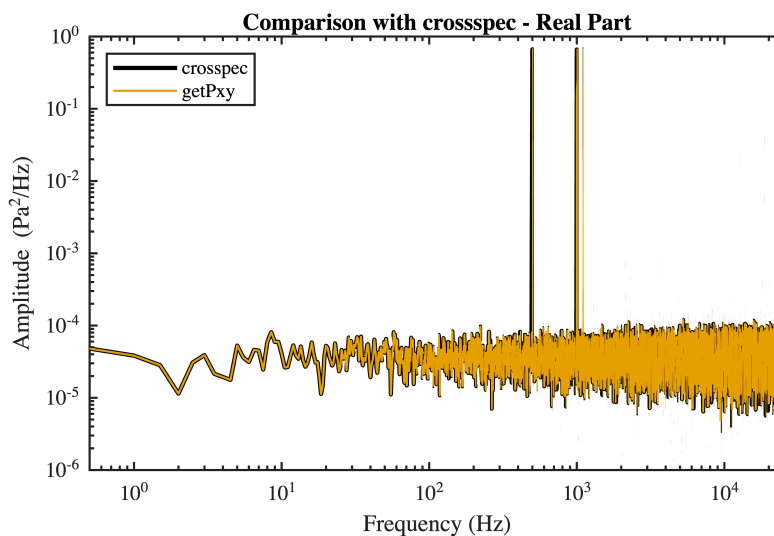
fs = 51200;
dt = 1/fs;
len = 10;
t = 0:dt:len;
x = randn(1,length(t));
x = x + sin(500 .* t * 2*pi) + sin(1000 .* t * 2*pi) + sin(1100 .* t * 2*pi);
y = x + randn(1,length(t))*0.5;

ns = fs*2;

[Gxy,fc] = crossspec_current(x,y,fs,ns,length(x),0);
[Pxy,fp] = getPxy(x,y,fs,'BlockSize',ns);

figure()
loglog(fc,real(Gxy),'DisplayName','crosspec','LineWidth',2); hold on
loglog(fp,real(Pxy),'DisplayName','getPxy','LineWidth',1)
xlim([min(fc),max(fc)])
legend('Location','northwest')
title('Comparison with crossspec - Real Part')
xlabel('Frequency (Hz)')
ylabel('Amplitude (Pa^2/Hz)')

```



```

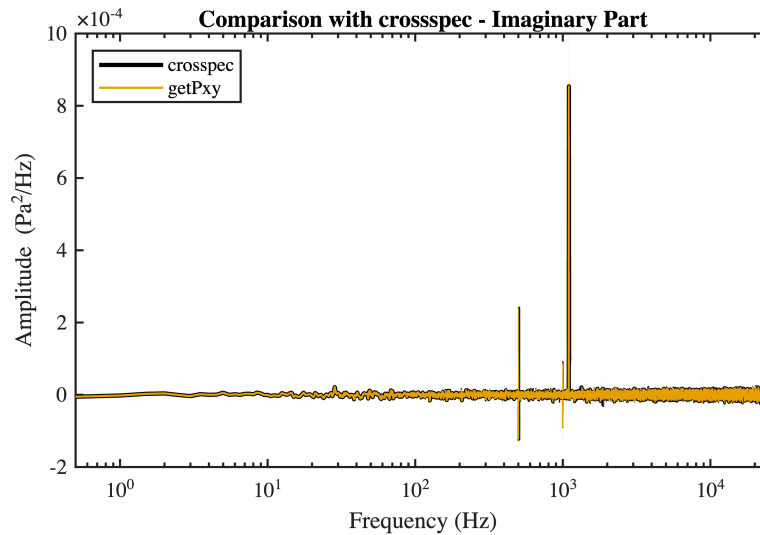
figure()
semilogx(fc,imag(Gxy),'DisplayName','crosspec','LineWidth',2); hold on
semilogx(fp,imag(Pxy),'DisplayName','getPxy','LineWidth',1)
xlim([min(fc),max(fc)])

```

```

legend('Location','northwest')
title('Comparison with crossspec - Imaginary Part')
xlabel('Frequency (Hz)')
ylabel('Amplitude (Pa^2/Hz)')

```



Now for the final verdict:

```
norm(real(Gxy)-real(Pxy))
```

```
ans =
0
```

```
norm(imag(Gxy)-imag(Pxy))
```

```
ans =
0
```

And just for good measure:

```
isequal(Gxy,Pxy)
```

```
ans = logical
1
```

Thus, the two functions produce numerically identical results.

getPxx() vs. autospec()

```

clear;

fs = 51200;
dt = 1/fs;
len = 10;
t = 0:dt:len;
x = randn(1,length(t));
x = x + sin(500 .* t * 2*pi) + sin(1000 .* t * 2*pi) + sin(1100 .* t *
2*pi);

ns = fs*2;

% Last edited: 2016
[Gxx_original,fo,~] = autospec_original(x,fs,ns,length(x),0);

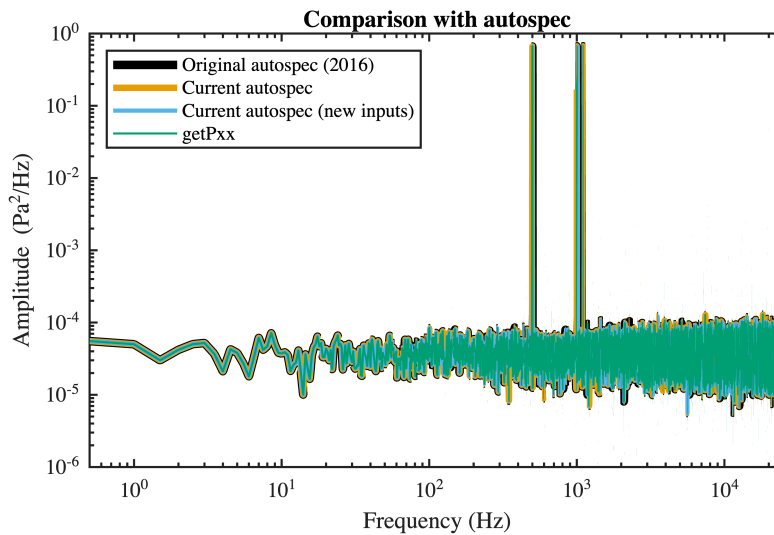
% Last edited: 2020
[Gxx_current,fa,~] = autospec_current(x,fs,ns,length(x),0);

% Last edited: 2020
[Gxx_current_new_inputs,fa2,~] = autospec_current(x,fs, ...
    'BlockSize',ns, ...
    'Length',length(x), ...
    'Output','Autospectral Density');

% COBRA Equivalent
[Pxx,fc] = getPxx(x,fs,'BlockSize',ns);

figure()
loglog(fo,Gxx_original,'DisplayName','Original autospec
(2016)','LineWidth',4); hold on
loglog(fa,Gxx_current,'DisplayName','Current autospec','LineWidth',3)
loglog(fa2,Gxx_current_new_inputs,'DisplayName','Current autospec (new
inputs)','LineWidth',2)
loglog(fc,Pxx,'DisplayName','getPxx','LineWidth',1)
xlim([min(fo),max(fo)])
title('Comparison with autospec')
legend('Location','northwest')
xlabel('Frequency (Hz)')
ylabel('Amplitude (Pa^2/Hz)')

```



Now for the final verdict:

```
norm(Gxx_original - Gxx_current)
```

```
ans =  
0
```

```
norm(Gxx_original - Pxx)
```

```
ans =  
0
```

```
norm(Gxx_current - Pxx)
```

```
ans =  
0
```

```
norm(Gxx_current_new_inputs - Pxx)
```

```
ans =  
0
```

Again for good measure:

```
isequal(Gxx_original,Gxx_current)
```

```
ans = logical  
1
```

```
isequal(Gxx_original,Pxx)
```

```
ans = logical  
1
```

```
isequal(Gxx_current,Pxx)
```

```
ans = logical  
1
```

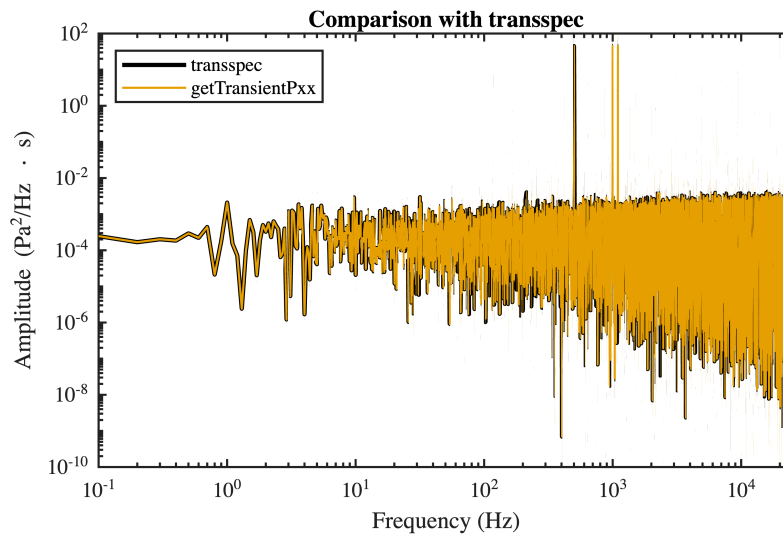
```
isequal(Gxx_current_new_inputs,Pxx)
```

```
ans = logical  
1
```

Thus, all functions produce numerically identical output.

getTransientPxx() vs. transspec()

```
clear;  
  
fs = 51200;  
dt = 1/fs;  
len = 10;  
t = 0:dt:len;  
x = randn(1,length(t));  
x = x + sin(500 .* t * 2*pi) + sin(1000 .* t * 2*pi) + sin(1100 .* t *  
2*pi);  
  
[Gxx,ft] = transspec_current(x,fs,'Taper',0.1,'ZeroPad',0);  
[Pxx,fp] = getTransientPxx(x,fs,'Output','Exposure');  
  
figure()  
loglog(ft,Gxx,'DisplayName','transspec','LineWidth',2); hold on  
loglog(fp,Pxx,'DisplayName','getTransientPxx','LineWidth',1)  
xlim([min(ft),max(ft)])  
title('Comparison with transspec')  
legend('Location','northwest')  
xlabel('Frequency (Hz)')  
ylabel('Amplitude (Pa^2/Hz \cdot s)')
```



Now for the final verdict:

```
norm(Gxx - Pxx)
```

```
ans =  
1.0049e-14
```

```
min(Gxx - Pxx)
```

```
ans =  
-7.1054e-15
```

```
max(Gxx - Pxx)
```

```
ans =  
0
```

The tiny difference is the same as zero for practical purposes.

Appendix C

Contributions to Other Publications

In this Appendix, I have described my contributions to a variety of peer-papers produced during my graduate program. I want to highlight that our research group, and rocket noise research in particular, has been highly collaborative. Thus, I have had the opportunity to contribute to many papers over the past several years.

I also note that for some papers, my primary contributions are in the realm of data collection. Although the data collection can seem like a small contribution, it often represents tremendous effort. For example, designing a field-test campaign involves predictive modeling to determine appropriate hardware, comprehensive testing and configuring of measurement equipment, and navigating a multitude of practical problems of being in the field. As one of our group's early rocket-noise members, I have often found myself in significant leadership roles on field tests, where I made important contributions to collecting the data that were ultimately used for analyses in the final papers.

As a rough gauge of how important my contributions (field work, data analysis, and/or writing) were to the final published papers, the reader is encouraged to observe my location in the author lists. It has been my experience that my location in the author list tends to correspond well to my relative contributions to each paper. While I do not list it for each publication, it is also safe to assume that, for each paper, I either contributed to the actual writing and editing of the paper or provided significant expertise that shaped the final results. As an author, I accept responsibility for the results along with the other authors.

Falcon 9 ascent sonic boom measurements in Ventura County, California

Abstract:

Reports of audible sonic booms along the south-central California coast during SpaceX Falcon 9 launch ascents prompted measurements in Ventura County during summer 2024. A total of 132 measurements were made over six launches, with 16–25 measurements per launch. The maximum overpressure measured was 1.90 psf (133 dB), but most measured booms had an overpressure below 0.5 psf and durations of several seconds. Two launches had appreciably lower overpressures and smaller terrestrial footprint, indicating that both meteorology and launch azimuth are important

factors in terrestrial boom audibility. Agreement between this dataset and environmental assessment predictions was marginal.

Full Citation:

K. L. Gee, M. S. Kellison, M. C. Anderson, L. T. Moats, M. T. Perkins, N. L. Pulsipher, N. F. Carlston, G. W. Hart, L. K. Hall, O. Cantrell, H. J. Zepeda Villanueva, M. R. McCullah-Boozer, R. H. Budge, J. C. King, F. A. Zering, Z. T. Zounes, K. C. Mackenthun, “Falcon 9 ascent sonic boom measurements in Ventura County, California.” *JASA Express Lett.* 6, 033601 (2026) <https://doi.org/10.1121/10.0043007>

Contribution:

Responsible for processing all measured acoustic data (Figs. 2–3), including developing a workflow for dealing with a type of sonic boom that was unfamiliar to us.

Starship Super Heavy acoustics: Comparing launch noise from Flights 5 and 6

Abstract:

This Letter analyzes launch noise from Starship Super Heavy’s Flights 5 and 6. While Flight-5 data covered 9.7–35.5 km, the stations during Flight 6 spanned 1.0–35.5 km. A comparison of A-weighted and unweighted maximum and exposure levels is made between flights and with an updated environmental assessment (EA). Key findings include: (a) the two flights’ noise levels diverge beyond 10 km, (b) EA models overestimate A-weighted metrics, and (c) the acoustic energy from a Starship launch is equivalent to 2.2 Space Launch System launches or ~11 Falcon 9 launches. These measurements help predict Starship’s noise levels around Kennedy Space Center.

Full Citation:

K. L. Gee, N. L. Pulsipher, M. S. Kellison, G. W. Hart, L. T. Mathews, M. C. Anderson, “Starship Super Heavy acoustics: Comparing launch noise from Flights 5 and 6.” *JASA Express Lett.* 5, 023602 (2025) <https://doi.org/10.1121/10.0035925>

Contribution:

Responsible for data collection.

Starship super heavy acoustics: Far-field noise measurements during launch and the first-ever booster catch

Abstract:

Far-field (9.7–35.5 km) noise measurements were made during the fifth flight test of SpaceX’s Starship Super Heavy, which included the first-ever booster catch. Key results involving launch and flyback sonic boom sound levels include (a) A-weighted sound exposure levels during launch are 18 dB less than predicted at 35 km; (b) the flyback sonic boom exceeds 10 psf at 10 km; and

(c) comparing Starship launch noise to Space Launch System and Falcon 9 shows that Starship is substantially louder; the far-field noise produced during a Starship launch is at least ten times that of Falcon 9.

Full Citation:

K. L. Gee, N. L. Pulsipher, M. S. Kellison, L. T. Mathews, M. C. Anderson, G. W. Hart, “Starship super heavy acoustics: Far-field noise measurements during launch and the first-ever booster catch.” JASA Express Lett. 4, 113601 (2024) <https://doi.org/10.1121/10.0034453>

Contribution:

Responsible for the sonic boom analysis.

Space Launch System acoustics: Far-field noise measurements of the Artemis-I launch

Abstract:

To improve understanding of super heavy-lift rocket acoustics, this letter documents initial findings from noise measurements during liftoff of the Space Launch System’s Artemis-I mission. Overall sound pressure levels, waveform characteristics, and spectra are described at distances ranging from 1.5 to 5.2 km. Significant results include: (a) the solid rocket boosters’ ignition overpressure is particularly intense in the direction of the pad flame trench exit; (b) post-liftoff maximum overall levels range from 127 to 136 dB, greater than pre-launch predictions; and (c) the average maximum one-third-octave spectral peak occurred at 20 Hz, causing significant deviation between flat and A-weighted levels.

Full Citation:

K. L. Gee, G. W. Hart, C. F. Cunningham, M. C. Anderson, M. S. Bassett, L. T. Mathews, J. T. Durrant, L. T. Moats, W. L. Coyle, M. K. Kellison, M. J. Kuffskie, “Space Launch System acoustics: Far-field noise measurements of the Artemis-I launch.” JASA Express Lett. 3, 023601 (2023) <https://doi.org/10.1121/10.0016878>

Contribution:

Responsible for data analysis, figure creation, and measurement efforts.

Saturn-V sound levels: A letter to the Redditor

Abstract:

The Saturn V is a monument to one of mankind’s greatest achievements: the human Moon landings. However, online claims about this vehicle’s impressive acoustics by well-meaning individuals are often based on misunderstood or incorrect data. This article, intended for both educators and enthusiasts, discusses topics related to rocket acoustics and documents what is known about the

Saturn V's levels: overall power, maximum overall sound pressure, and peak pressure. The overall power level was approximately 204 dB re 1 pW, whereas its lesser sound pressure levels were impacted by source size, directivity, and propagation effects. As this article is part of a special issue on Education in Acoustics in The Journal of the Acoustical Society of America, supplementary Saturn V-related homework problems are included.

Full Citation:

K. L. Gee, L. T. Mathews, M. C. Anderson, G. W. Hart, "Saturn-V sound levels: A letter to the Redditor", J. Acoust. Soc. Am. 152, 1068-1073 (2022) <https://doi.org/10.1121/10.0013216>

Contribution:

Responsible for the supplementary material homework solutions.

Sonic boom measurements: Practical implications considering ground effects, microphone installation and weather-hardening**Abstract:**

Sonic boom measurements from recent flight tests have provided an opportunity to investigate effects of microphone installation on sonic boom waveforms, spectra, and metric levels in support of NASA X-59 flight test planning. While those flight tests used N-wave aircraft (F-18s), modeling studies were also conducted using source characteristics for a shaped low-boom aircraft. Of particular interest were the effects of receiver height on boom waveforms and metrics at elevated receiver positions, microphone installation, and local ground cover type. Reductions of more than 2 dB in A-weighted sound exposure level and perceived level were shown for 1.6 ft (0.48 m) microphone heights for 35° ray elevation angle. Measured and modeled results are described in this letter.

Full Citation:

R. Downs, J. Page, J. T. Durrant, K. L. Gee, D. J. Novakovich, M. C. Anderson, A. Loubeau, "Sonic boom measurements: Practical implications considering ground effects, microphone installation and weather-hardening." JASA Express Lett. 2 (10), 104001 (2022) <https://doi.org/10.1121/10.0014414>

Contribution:

Responsible for a portion of the preliminary measurements that contributed to the ideas behind this publication.

Bibliography

- Aerostar Environmental Services (2007). “Environmental Assessment for the operation and launch of the Falcon 1 and Falcon 9 Space Vehicles at Cape Canaveral Air Force Station Florida,” URL: <https://netspublic.grc.nasa.gov/main/Final%20Falcon%201and9%20EA%20Nov%202007.pdf>.
- Alden, H. L., and Habert, R. H. (1964). “Gas Dynamics of High-Altitude Rocket Plumes,” AFCRL-64-677, URL: <https://apps.dtic.mil/sti/tr/pdf/AD0607940.pdf>.
- Anderson, J. D. (2017). McGraw-Hill Series in Aeronautical and Aerospace Engineering *Fundamentals of Aerodynamics*, 6th ed. (McGraw-Hill Education).
- Anderson, M. C., and Gee, K. L. (2024). “Sonic Boom Measurements From the SpaceX Transporter-8 Falcon-9 Rocket Landing at Vandenberg Space Force Base,” 30th AIAA/CEAS Aeroacoustics Conference DOI:10.2514/6.2024-3188, URL: <https://arc.aiaa.org/doi/abs/10.2514/6.2024-3188> Corrections to a few errors in the manuscript can be found at <https://doi.org/10.2514/6.2024-3188.c1>.
- Anderson, M. C., and Gee, K. L. (2025a). “Modeling the SpaceX Falcon-9 Booster’s Triple Sonic Boom Using Multiple Models and Conditions” DOI:10.2514/6.2025-3081, URL: <https://doi.org/10.2514/6.2025-3081>.
- Anderson, M. C., and Gee, K. L. (2025b). “Why does the Falcon-9 booster make a triple sonic boom during flyback? An initial analysis,” JASA Express Lett. **5**(2), 023601, DOI:10.1121/10.0035649, URL: <https://doi.org/10.1121/10.0035649>.
- Anderson, M. C., Gee, K. L., Durrant, J. T., Loubeau, A., Doebler, W. J., and Klos, J. (2024a). “Recommendations for sonic boom community noise testing measurement and analysis,” Proc. Mtgs. Acoust. **50**(1), 040008, DOI:10.1121/2.0001902, URL: <https://doi.org/10.1121/2.0001902>.
- Anderson, M. C., Gee, K. L., Durrant, J. T., Loubeau, A., Doebler, W. J., and Klos, J. (2024b). “Reducing contaminating noise effects when calculating low-boom loudness levels,” J. Acoust. Soc. Am. **155**(6), 3889–3899, DOI:10.1121/10.0026436, URL: <https://doi.org/10.1121/10.0026436>.
- Anderson, M. C., Gee, K. L., and Hall, L. L. (2025). “How the season affects if you hear a sonic boom during rocket ascent,” Acoustics Lay Language Paper URL: <https://acoustics.org/how-the-season-affects-if-you-hear-a-sonic-boom-during-rocket-ascent>.

- Anderson, M. C., Gee, K. L., Novakovich, D. J., Mathews, L. T., and Jones, Z. T. (2022a). "Comparing two weather-robust microphone configurations for outdoor measurements," *Proc. Mtgs. Acoust.* **42**(1), 040005, DOI:10.1121/2.0001561, URL: <https://doi.org/10.1121/2.0001561>.
- Anderson, M. C., Gee, K. L., Novakovich, D. J., Rasband, R. D., Mathews, L. T., Durrant, J. T., Leete, K. M., and Loubeau, A. (2022b). "High-fidelity sonic boom measurements using weather-robust measurement equipment," *Proc. Mtgs. Acoust.* **39**(1), 040005, DOI:10.1121/2.0001578, URL: <https://doi.org/10.1121/2.0001578>.
- Anderson, M. C., Gee, K. L., and Nyborg, K. (2024c). "Flyback sonic booms from Falcon-9 rockets: Measured data and some considerations for future models," *Proc. Mtgs. Acoust.* **54**(1), 040005, DOI:10.1121/2.0001916, URL: <https://doi.org/10.1121/2.0001916>.
- Anderson, M. C., Stephenson, J. H., Zawodny, N. S., and Gee, K. L. (2021). "Characterizing the effects of two ground-based outdoor microphone configurations," *Proc. Mtgs. Acoust.* **39**(1), 055011, DOI:10.1121/2.0001388, URL: <https://doi.org/10.1121/2.0001388>.
- Anderson, M. O. (1974). "The propagation of a spherical N wave in an absorbing medium and its diffraction by a circular aperture," Technical Report No. ARL-TR-74-25.
- Andrews, E. H., Craidon, C. B., Dennard, J. S., and Vick, A. R. (1964). "Comparisons of Experimental Free-jet Boundaries with Theoretical Results Obtained with the Method of Characteristics," NASA TN D-2327, URL: <https://ntrs.nasa.gov/citations/19640013118>.
- ARDE Associates (1959). "Response of Structures to Aircraft Generated Shock Waves," U. S. Air Force WADC Tech. Rept. No. 58-169, URL: <https://apps.dtic.mil/sti/tr/pdf/AD0229463.pdf>.
- Ashby, G. C. (1979). "Near-Field Sonic-Boom Pressure Signatures for the Space Shuttle Launch and Orbiter Vehicles at Mach 6," NASA TP-1405, URL: <https://ntrs.nasa.gov/citations/19790012948>.
- Ashby, G. C. J. (1980). "A study of the sonic-boom characteristics of a blunt body at a Mach number of 6," NASA TP-1787, URL: <https://ntrs.nasa.gov/citations/19810005404>.
- Averiyarov, M., Ollivier, S., Khokhlova, V., and Blanc-Benon, P. (2011). "Random focusing of nonlinear acoustic N-waves in fully developed turbulence: Laboratory scale experiment," *J. Acoust. Soc. Am.* **130**(6), 3595–3607, DOI:10.1121/1.3652869, URL: <https://doi.org/10.1121/1.3652869>.
- Baars, W. J., Tinney, C. E., Wochner, M. S., and Hamilton, M. F. (2014). "On cumulative nonlinear acoustic waveform distortions from high-speed jets," *J. Fluid Mech.* **749**, 331–366, DOI:10.1017/jfm.2014.228, URL: <https://doi.org/10.1017/jfm.2014.228>.
- Bickmore, J. D., Gee, K. L., Perkins, M. T., Anderson, M. C., Hall, L. K., and Zepeda, H. (2025). "A year's worth of Falcon 9 Ascent sonic boom measurements in Southern California," *J. Acoust. Soc. Am.* **158**(4_supplement), A119, URL: <https://acousticalsociety.org/wp-content/uploads/2025/11/honolulu-programrevised1.pdf> DOI link not yet available.

- Bishop, D. E., Haber, J. M., and Wilby, E. G. (1988). "BOOMAP2 Computer Program for Sonic Boom Research: Technical Report, Volume I of III Volumes," HSD-TR-88-001, Vol. 1, URL: <https://apps.dtic.mil/sti/tr/pdf/ADA198892.pdf>.
- Bishop, J. W., Blom, P., Carr, C., and Webster, J. (2025). "An infrasound source analysis of the OSIRIS-REx sample return capsule hypersonic re-entry," *J. Acoust. Soc. Am.* **158**(6), 4637–4650, DOI:10.1121/10.0041857, URL: <https://doi.org/10.1121/10.0041857>.
- Bodony, D. J., and Lele, S. K. (2008). "Current Status of Jet Noise Predictions Using Large-Eddy Simulation," *AIAA Journal* **46**(2), 364–380, DOI:10.2514/1.24475, URL: <https://doi.org/10.2514/1.24475>.
- Boire, G. G., Daniel, O. H., de Violini, R., Finder, F. G., and Fisher, E. E. (1983). "Range Reference Atmosphere, 0–70 km Altitude, Vandenberg AFB, California," Metrology Group, Range Commanders Council. Document 362-83, URL: <https://ntrl.ntis.gov/NTRL/dashboard/searchResults/titleDetail/ADA128125.xhtml>.
- Borsky, P. N. (1965). "Community Reactions to Sonic Booms in the Oklahoma City Area," National Opinion Res. Ctr., AMRL Rept. TR-65-37, Repts. I and II, URL: <https://apps.dtic.mil/sti/pdfs/AD0613620.pdf>.
- Bradley, K. A., Hobbs, C. M., Wilmer, C. B., Sparrow, V. W., Stout, T. A., Morgenstern, J. M., Underwood, K. H., Maglieri, D. J., Cowart, R. A., Collmar, M. T., Shen, H., and Blanc-Benon, P. (2020). "Sonic Booms in Atmospheric Turbulence (SonicBAT): The Influence of Turbulence on Shaped Sonic Booms," NASA/CR-2020-220509, URL: <https://ntrs.nasa.gov/citations/20200002482>.
- Bradley, K. A., Smith, E. L., and Wilmer, C. B. (2021). "Starship Rocket Noise Assessment for Flight and Test Operations at the Boca Chica Launch Facility. Appendix B. Noise Assessment," URL: <https://www.faa.gov/sites/faa.gov/files/2022-06/AppendixB%5FNoiseAssessment.pdf>.
- Brown, D., and Sutherland, L. C. (1992). "Evaluation of outdoor-to-indoor response to minimized sonic booms," NASA CR-189643, URL: <https://ntrs.nasa.gov/citations/19920019313>.
- Bykerk, T., Kirchheck, D., and Karl, S. (2022). "Reconstruction of Wind Tunnel Tests using CFD for a Reusable First Stage during Rocket Retro-Propulsion," DOI:10.13009/EUCASS2022-4494, URL: <https://doi.org/10.13009/EUCASS2022-4494>.
- Campbell, J. F., and Chambers, J. R. (1994). "Patterns in the sky: Natural visualization of aircraft flow fields," NASA SP-514, URL: <https://ntrs.nasa.gov/citations/19950024579>.
- Carlson, H. W. (1978). "Simplified Sonic Boom Prediction," NASA TP-1122, URL: <https://ntrs.nasa.gov/citations/19780012135>.
- Carlson, H. W., and Mack, R. J. (1977). "A Study of the Sonic-Boom Characteristics of a Blunt Body at a Mach Number of 4.14," NASA TP-1015, URL: <https://ntrs.nasa.gov/citations/19770025128>.

- Carlson, H. W., and Mack, R. J. (1978). "A wind-tunnel study of the applicability of far-field sonic-boom theory to the space shuttle orbiter," NASA TP-1186, URL: <https://ntrs.nasa.gov/citations/19780017118>.
- Carlson, H. W., Mack, R. J., and Morris, O. A. (1965). "A wind-tunnel investigation of the effect of body shape on sonic-boom pressure distributions," NASA TN D-3106, URL: <https://ntrs.nasa.gov/citations/19660001963>.
- Carlson, H. W., and Maglieri, D. J. (1972). "Review of sonic-boom generation theory and prediction methods," J. Acoust. Soc. Am. **51**(2C), 675–685, DOI:10.1121/1.1912901, URL: <https://doi.org/10.1121/1.1912901>.
- Carr, A. N., Lonzaga, J. B., and Miller, S. A. E. (2022). "Numerical prediction of loudness metrics for N-waves and shaped sonic booms in kinematic turbulence," J. Acoust. Soc. Am. **151**(6), 3580–3593, DOI:10.1121/10.0011514, URL: <https://doi.org/10.1121/10.0011514>.
- CCCS (2023). "Copernicus Climate Change Service, Climate Data Store: ERA5 hourly data on single levels from 1940 to present" DOI:10.24381/cds.adbb2d47, URL: <https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=overview>, Copernicus Climate Change Service (C3S) Climate Data Store (CDS).
- Charbonnier, D., Vos, J., Marwege, A., and Hantz, C. (2022). "Computational fluid dynamics investigations of aerodynamic control surfaces of a vertical landing configuration," CEAS Space Journal **14**, 517–532, DOI:10.1007/s12567-022-00431-6, URL: <https://doi.org/10.1007/s12567-022-00431-6>.
- Cheng, D. H., and Benveniste, J. E. (1969). "Dynamic response of structural elements exposed to sonic booms," NASA CR-1281, URL: <https://ntrs.nasa.gov/citations/19690012041>.
- Christian, M. A., Gee, K. L., Streeter, J. B., Wall, A. T., and Campbell, S. C. (2023). "Sound power and acoustic efficiency of an installed GE F404 jet engine," JASA Express Lett. **3**(7), 073601, DOI:10.1121/10.0019866, URL: <https://doi.org/10.1121/10.0019866>.
- Clarkson, B. L., and Mayes, W. H. (1972). "Sonic-Boom-Induced Building Structure Responses Including Damage," J. Acoust. Soc. Am. **51**(2C), 742–757, DOI:10.1121/1.1912907, URL: <https://doi.org/10.1121/1.1912907>.
- Cleveland, R. O., and Blackstock, D. T. (1996). "Waveform Freezing of Sonic Booms Revisited," in *1995 NASA High-Speed Research Program Sonic Boom Workshop*, edited by D. G. Baize, Vol. 1, pp. 20–40, URL: <https://ntrs.nasa.gov/citations/19960055051>.
- Cole, J. N., Kyrazis, D. T., and Oestreicher, H. L. (1956). "A method for calculating the acoustical characteristics of aircraft in flight," WADC TN 56-488, URL: <https://contrails.library.iit.edu/item/155692>.

- Cole, J. N., Von Gierk, H. E., Kyrazis, D. T., Eldred, K. M., and Humphrey, A. J. (1957). "Noise Radiation from Fourteen Types of Rockets in the 1,000 to 130,000 Pounds Thrust Range," WADC Technical Report 57-354.
- Cook, M. R., Gee, K. L., Transtrum, M. K., Lympany, S. V., and Calton, M. (2021). "Automatic classification and reduction of wind noise in spectral data," *JASA Express Lett.* **1**(6), 063602, DOI:10.1121/10.0005308, URL: <https://doi.org/10.1121/10.0005308>.
- Cotten, D., and Donn, W. L. (1971). "Sound from Apollo Rockets in Space," *Science* **171**(3971), 565–567, DOI:10.1126/science.171.3971.565, URL: <https://www.science.org/doi/abs/10.1126/science.171.3971.565>.
- Cotten, D. E., Donn, W. L., and Oppenheim, A. (1971). "On the Generation and Propagation of Shock Waves From Apollo Rockets at Orbital Altitudes," *Geophysical Journal International* **26**(1-4), 149–159, DOI:10.1111/j.1365-246X.1971.tb03388.x, URL: <https://doi.org/10.1111/j.1365-246X.1971.tb03388.x>.
- Cour-Palais, B. G. (1977). "Proceedings of the Space Shuttle Environmental Assessment Workshop on Tropospheric Effects," NASA TM X-58199 JSC-11769, URL: <https://ntrs.nasa.gov/citations/19770016684>.
- Cunningham, C., Anderson, M. C., Moats, L. T., Gee, K. L., Hart, G. W., and Hall, L. K. (2023). "Acoustical measurement and analysis of an Atlas V launch," *Proc. Mtgs. Acoust.* **46**(1), 045005, DOI:10.1121/2.0001742, URL: <https://doi.org/10.1121/2.0001742>.
- Czarnecki, K., and Jackson, M. W. (1975). "Turbulent Boundary-Layer Separation due to a Forward-Facing Step," *AIAA Journal* **13**(12), 1585–1591, DOI:10.2514/3.60582, URL: <https://doi.org/10.2514/3.60582>.
- Direct, C. (2025). "Notes on Computational Fluid Dynamics: General Principles" URL: <https://doc.cfd.direct/notes/cfd-general-principles/specific-dissipation-rate>, Last Viewed: 04-21-2025.
- Doebler, W., and Loubeau, A. (2023). "A procedure for obtaining forecast turbulence parameters in the atmospheric boundary layer for acoustic propagation," *J. Acoust. Soc. Am.* **154**(4_supplement), A147–A147, DOI:10.1121/10.0023075, URL: <https://doi.org/10.1121/10.0023075> Slides available at <https://ntrs.nasa.gov/citations/20230017081>.
- Doebler, W. J. (2017). "The Minimum Number of Ground Measurements Required for Narrow Sonic Boom Metric 90% Confidence Intervals," Thesis, The Pennsylvania State University, URL: <https://etda.libraries.psu.edu/catalog/14826wfd5057>.
- Doebler, W. J. (2021). "Estimated ambient sonic boom metric levels and X-59 signal-to-noise ratios across the USA," *Proc. Mtgs. Acoust.* **42**(1), 040003, DOI:10.1121/2.0001405, URL: <https://doi.org/10.1121/2.0001405>.

- Doebler, W. J., and Rathsam, J. (2020). "How loud is X-59's shaped sonic boom?," *Proc. Mtgs. Acoust.* **36**(1), 040005, DOI:10.1121/2.0001265, URL: <https://doi.org/10.1121/2.0001265>.
- Doebler, W. J., Wilson, S. R., Loubeau, A., and Sparrow, V. W. (2022). "Simulation and Regression Modeling of NASA's X-59 Low-Boom Carpets Across America," *Journal of Aircraft* **60**(2), 509–520, DOI:10.2514/1.C036876, URL: <https://doi.org/10.2514/1.C036876>.
- Downing, J. M., and Plotkin, K. (1996). "Validation of launch vehicle sonic boom predictions," *J. Acoust. Soc. Am.* **100**(4_Supplement), 2566–2566, DOI:10.1121/1.417381, URL: <https://doi.org/10.1121/1.417381>.
- Downing, M., Zamot, N., Moss, C., Morin, D., Wolski, E., Chung, S., Plotkin, K., and Maglieri, D. J. (1996). "USAF Flight Investigation of Focused Sonic Booms; Project HAVE BEARs," NASA CP-3335, pp. 259-277, URL: <https://ntrs.nasa.gov/citations/19960055049>.
- Downs, R., Page, J., Durrant, J. T., Gee, K. L., Novakovich, D. J., Anderson, M. C., and Loubeau, A. (2022). "Sonic boom measurements: Practical implications considering ground effects, microphone installation, and weather hardening," *JASA Express Letters* **2**(10), 104001, DOI:10.1121/10.0014414, URL: <https://doi.org/10.1121/10.0014414>.
- Drob, D. P., Emmert, J. T., Meriwether, J. W., Makela, J. J., Doornbos, E., Conde, M., Hernandez, G., Noto, J., Zawdie, K. A., McDonald, S. E., Huba, J. D., and Klenzing, J. H. (2015). "An update to the Horizontal Wind Model (HWM): The quiet time thermosphere," *Earth and Space Science* **2**(7), 301–319, DOI:10.1002/2014EA000089, URL: <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2014EA000089>.
- Durrant, J. T., Anderson, M. C., Bassett, M. S., Gee, K. L., Hart, G. W., Batelaan, R. H., Lawrence, D. C., and Hall, L. K. (2023). "Overview and spectral analysis of the Falcon-9 SARah-1 launch and reentry sonic boom," *Proc. Mtgs. Acoust.* **51**(1), 040006, DOI:10.1121/2.0001767, URL: <https://doi.org/10.1121/2.0001767>.
- Durrant, J. T., Anderson, M. C., Gee, K. L., Mathews, L. T., and Hart, G. W. (2022a). "Initial comparison of a Falcon-9 reentry sonic boom with other launch-related noise," *Proc. Mtgs. Acoust.* **46**(1), 045002, DOI:10.1121/2.0001579, URL: <https://doi.org/10.1121/2.0001579>.
- Durrant, J. T., Gee, K. L., Anderson, M. C., Mathews, L. T., Rasband, R. D., Novakovich, D. J., Loubeau, A., and Doebler, W. J. (2022b). "An overview of Brigham Young University's participation in NASA's CarpetDIEM campaign," *Proc. Mtgs. Acoust.* **43**(1), 045002, DOI:10.1121/2.0001589, URL: <https://doi.org/10.1121/2.0001589>.
- Durre, I., Vose, R. S., and Wuertz, D. B. (2006). "Overview of the Integrated Global Radiosonde Archive," *Journal of Climate* **19**(1), 53 – 68, DOI:10.1175/JCLI3594.1, URL: <https://doi.org/10.1175/JCLI3594.1>.

- Eldred, K. M. (1971). "Acoustic Loads Generated by the Propulsion System," NASA SP-8072, URL: <https://ntrs.nasa.gov/citations/19710023719>.
- Esparza, E. D., and Baker, W. E. (1977). "Measurement of Blast Waves from Bursting Pressurized Frangible Spheres," NASA CR-2843, URL: <https://ntrs.nasa.gov/citations/19770017362>.
- FAA (1998). "Final Environmental Impact Statement: Evolved Expendable Launch Vehicle Program," URL: <https://www.faa.gov/about/office%5Forg/headquarters%5Foffices/ast/licenses%5Fpermits/media/EIS1998-AF.pdf>.
- FAA (2000). "Final Supplemental Environmental Impact Statement for the Evolved Expendable Launch Vehicle Program," URL: <https://www.faa.gov/about/office%5Forg/headquarters%5Foffices/ast/licenses%5Fpermits/media/eelvSEis.pdf>.
- FAA (2020a). "Final Environmental Assessment and Finding of No Significant Impact for SpaceX Falcon Launches at Kennedy Space Center and Cape Canaveral Air Force Station," URL: <https://www.faa.gov/sites/faa.gov/files/space/environmental/nepa%5Fdocs/SpaceX%5FFalcon%5FProgram%5FFinal%5FEA%5Fand%5FFONSI.pdf>.
- FAA (2020b). "Final Environmental Assessment and Finding of No Significant Impact for SpaceX Falcon Launches at Kennedy Space Center and Cape Canaveral Air Force Station, Appendix A," URL: <https://www.faa.gov/sites/faa.gov/files/space/environmental/nepa%5Fdocs/Falcon%5FProgram%5FEA%5FAppendices%5F508.pdf>.
- Ferri, A., Ting, L., and Lo, R. (1976). "Nonlinear sonic boom analysis including the asymmetric effects," DOI:10.2514/6.1976-587, URL: <https://doi.org/10.2514/6.1976-587>.
- Ffowcs Williams, J. E. (1963). "The noise from turbulence convected at high speed," *Philosophical Transactions of the Royal Society of London, Series A: Mathematical and Physical Sciences* **255**(1061), 469–503, DOI:10.1098/rsta.1963.0010, URL: <https://doi.org/10.1098/rsta.1963.0010>.
- Francine, J. K., and Stewart, B. S. (1995). "Sonic boom from the Titan IV space launch vehicle launched from Vandenberg Air Force Base," *J. Acoust. Soc. Am.* **97**(5_Supplement), 3258–3258, DOI:10.1121/1.411685, URL: <https://doi.org/10.1121/1.411685>.
- Franken, P. A. (1958). "Review of Information on Jet Noise," *Noise Control* **4**(3), 8–16, DOI:10.1121/1.2369320, URL: <https://doi.org/10.1121/1.2369320>.
- Franquet, E., Perrier, V., Gibout, S., and Bruel, P. (2015). "Free underexpanded jets in a quiescent medium: A review," *Progress in Aerospace Sciences* **77**, 25–53, DOI:10.1016/j.paerosci.2015.06.006, URL: <https://doi.org/10.1016/j.paerosci.2015.06.006>.
- Garcia, F., and Potter, A. E. (1983). "Sonic Booms from the Launch and Landing of the Space Shuttle," *Space Shuttle Environmental Effects: The First 5 Flights*. NASA CR-171812 JSC-19091, URL: <https://ntrs.nasa.gov/citations/19850002149>.

- Garcia, F. J., Hicks, R. M., and Mendoza, J. P. (1973). "A wind tunnel flight correlation of Apollo 16 sonic boom," NASA TM X-62073, URL: <https://ntrs.nasa.gov/citations/19730012346>.
- Garcia, F. J., Jones, J. H., and Henderson, H. R. (1983a). "A comparison of measured and theoretical predictions for STS ascent and entry sonic booms," Shuttle Performance: Lessons Learned, Part 2. NASA CP-2283-PT-2, URL: <https://ntrs.nasa.gov/citations/19840002101>.
- Garcia, F. J., Jones, J. H., and Henderson, H. R. (1983b). "Preliminary Sonic Boom Correlations of Predicted and Measured Levels for STS-5 launch," NASA TM-58253, URL: Not Publicly Available.
- Garcia, F. J., Jones, J. H., and Henderson, H. R. (1985). "Correlation of predicted and measured sonic boom characteristics from the reentry of STS-1 Orbiter," NASA-TP-2475, URL: <https://ntrs.nasa.gov/citations/19850021382>.
- Garcia, F. J., Morrison, K. M., Jones, J. H., and Henderson, H. R. (1982). "Preliminary sonic boom correlation of predicted and measured levels for STS-1 entry," NASA TM-58242, URL: <https://ntrs.nasa.gov/citations/19820013160>.
- Gee, K. L. (2005). "Prediction of nonlinear jet noise propagation," Dissertation, The Graduate Program in Acoustics at Pennsylvania State University, URL: <https://etda.libraries.psu.edu/catalog/6736>.
- Gee, K. L., Anderson, M. C., Durrant, J. T., Blaine, J. D., Nyborg, K., and Sorrell, A. K. (2024a). "Sonic Boom Analyses in Support of Improved X-59 Community Noise Testing," NASA/CR-20240008985, URL: <https://ntrs.nasa.gov/citations/20240008985>.
- 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 acoustics: Far-field noise measurements of the Artemis-I launch," JASA Express Lett. **3**(2), 023601, DOI:10.1121/10.0016878, URL: <https://doi.org/10.1121/10.0016878>.
- Gee, K. L., Kellison, M. S., Anderson, M. C., Moats, L. T., Perkins, M. T., Pulsipher, N. L., Carlston, N. F., Hart, G. W., Hall, L. K., Cantrell, O., Villanueva, H. J. Z., McCullah-Boozer, M. R., Budge, R. H., King, J. C., Zering, F. A., Zounes, Z. T., and Mackenthun, K. C. (2026). "Falcon 9 ascent sonic boom measurements in Ventura County, California," JASA Express Lett. **6**(3), 033601, DOI:10.1121/10.0043007, URL: <https://doi.org/10.1121/10.0043007>.
- Gee, K. L., Kenny, R. J., Neilsen, T. B., Jerome, T. W., Hobbs, C. M., and James, M. M. (2013). "Spectral and statistical analysis of noise from reusable solid rocket motors," Proc. Mtgs. Acoust. **18**(1), 040002, DOI:10.1121/1.4789401, URL: <https://doi.org/10.1121/1.4789401>.
- Gee, K. L., Neilsen, T. B., and James, M. M. (2014). "Including source correlation and atmospheric turbulence in a ground reflection model for rocket noise," Proc. Mtgs. Acoust. **22**(1), 040001, DOI:10.1121/2.0000002, URL: <https://doi.org/10.1121/2.0000002>.

- Gee, K. L., Novakovich, D. J., Mathews, L. T., Anderson, M. C., and Rasband, R. D. (2020). "Development of a Weather-Robust Ground-Based System for Sonic Boom Measurements," NASA/CR-20205001870, URL: <https://ntrs.nasa.gov/citations/20205001870>.
- Gee, K. L., Olaveson, T. W., and Mathews, L. T. (2025). "Convective Mach Number and Full-Scale Supersonic Jet Noise Directivity," AIAA Journal **63**(4), 1393–1404, DOI:10.2514/1.J064208, URL: <https://doi.org/10.2514/1.J064208>.
- Gee, K. L., Pulsipher, N. L., Kellison, M. S., Mathews, L. T., Anderson, M. C., and Hart, G. W. (2024b). "Starship super heavy acoustics: Far-field noise measurements during launch and the first-ever booster catch," JASA Express Lett. **4**(11), 113601, DOI:10.1121/10.0034453, URL: <https://doi.org/10.1121/10.0034453>.
- Gee, K. L., Sparrow, V. W., James, M. M., Downing, J. M., Hobbs, C. M., Gabrielson, T. B., and Atchley, A. A. (2008). "The role of nonlinear effects in the propagation of noise from high-power jet aircraft," J. Acoust. Soc. Am. **123**(6), 4082–4093, DOI:10.1121/1.2903871, URL: <https://doi.org/10.1121/1.2903871>.
- Geuzaine, C., and Remacle, J. (2024). "Gmsh" URL: <https://gmsh.info/>, Last viewed: 05-29-2025.
- Glatt, C. R., Hague, D. S., and Reiners, S. J. (1975a). "Prediction of sonic boom from experimental near-field overpressure data. Volume I – Method and Results," NASA CR-2441, URL: <https://ntrs.nasa.gov/citations/19750008243>.
- Glatt, C. R., Hague, D. S., and Reiners, S. J. (1975b). "Prediction of sonic boom from experimental near-field overpressure data. Volume II – Data Base Construction," NASA CR-2442, URL: <https://ntrs.nasa.gov/citations/19750007583>.
- Gottlieb, J. J., and Ritzel, D. V. (1988). "Analytical study of sonic boom from supersonic projectiles," Progress in Aerospace Sciences **25**(2), 131–188, DOI:10.1016/0376-0421(88)90006-1, URL: [https://doi.org/10.1016/0376-0421\(88\)90006-1](https://doi.org/10.1016/0376-0421(88)90006-1).
- GRAS (2024a). "GRAS 46BE 1/4" CCP Free-field Standard Microphone Set" URL: <https://www.grasacoustics.com/products/measurement-microphone-sets/constant-current-power-ccp/product/143-46be>, Last Viewed: 02-12-2026.
- GRAS (2024b). "GRAS 47AC 1/2" CCP Infra-Sound Microphone Set" URL: <https://www.grasacoustics.com/products/special-microphone/infra-sound-microphones/product/712-47ac>, Last Viewed: 02-12-2026.
- Green, K. S., and Putnam, T. W. (1974). "Measurements of sonic booms generated by an airplane flying at Mach 3.5 and 4.8," NASA TM X-3126, URL: <https://ntrs.nasa.gov/citations/19740026373>.
- Green-Lanchoney, J. (2025). "VSFB Pioneers Research on Ascent Sonic Booms" URL: <https://www.vandenberg.spaceforce.mil/News/Article-Display/Article/4188018/>

- [vsfb-pioneers-research-on-ascent-sonic-booms/](#), Space Launch Delta 30 Public Affairs, Vandenberg Space Force Base. Last Viewed: 02-07-2026.
- Green-Lanchoney, J. (2026). "Space Force Teams with Universities to Advance Sonic Boom Research in California." URL: <https://www.vandenberg.spaceforce.mil/News/Article-Display/Article/4380022/space-force-teams-with-universities-to-advance-sonic-boom-research-in-california/>, Space Launch Delta 30 Public Affairs, Vandenberg Space Force Base. Last Viewed: 02-07-2026.
- Guest, S. H. (1964). "Acoustic efficiency trends for high thrust boosters," NASA TN D-1999.
- Gurbatov, S. N., and Rudenko, O. V. (2024). *Statistical Phenomena* (Springer Cham), URL: <https://doi.org/10.1007/978-3-031-58963-8>, Chapter 13 in "Nonlinear Acoustics" edited by Hamilton and Blackstock.
- Haber, J., and Nakaki, D. (1989). "Sonic Boom Damage to Conventional Structures," SAF HSD-TR-89-001, URL: <https://apps.dtic.mil/sti/tr/pdf/ADA213594.pdf>.
- Haber, J. M. (1981). "Parametric Evaluation of Sonic Booms Resulting from the Ascent Phase of STS Launches from Vandenberg Air Force Base," TR 81-3076-1 J. H. Wiggins Co., URL: Not Publicly Available.
- Hamilton, M. F., and Blackstock, D. T. (2024). *Nonlinear Acoustics* (Springer Cham), URL: <https://doi.org/10.1007/978-3-031-58963-8>, ISBN: 978-3-031-58962-1.
- Hansen, J., Connolly, P., Larkin, J., Preston, B., Lelchuk, P., Chwiedor, T., and Chelkis, F. (2011). "Incorporation of RD-180 Failure Response Features in the Atlas V Booster Emergency Detection System," DOI:10.2514/6.2011-7120, URL: <https://doi.org/10.2514/6.2011-7120> Also available at <https://www.ulalaunch.com/docs/default-source/supporting-technologies/incorporation-of-rd-180-failure-response-2011.pdf>.
- Harrison, T., Hunter, A., Johnson, K., Linck, E., and Roberts, T. (2017). "Beyond the RD-180," A Report of the CSIS Aerospace Security Project., URL: <https://csis-website-prod.s3.amazonaws.com/s3fs-public/publication/170321%5FHarrison%5FBeyondRD180%5FWeb.pdf>.
- Hart, G. W., and Gee, K. L. (2023). "Correcting for ground reflections when measuring overall sound power level and acoustic radiation efficiency of rocket launches," Proc. Mtgs. Acoust. **50**(1), 040004, DOI:10.1121/2.0001733, URL: <https://doi.org/10.1121/2.0001733>.
- Hart, G. W., Mathews, L. T., Anderson, M. C., Durrant, J. T., Bassett, M. S., Olausson, S. A., Houston, G., and Gee, K. L. (2022). "Methods and results of acoustical measurements made of a Delta IV Heavy launch," Proc. Mtgs. Acoust. **45**(1), 040003, DOI:10.1121/2.0001580, URL: <https://doi.org/10.1121/2.0001580>.
- Hayes, W. D. (1967). "Brief Review of the Basic Theory," in *Sonic Boom Research*, edited by A. R. Seebass, NASA, pp. 3–7, URL: <https://ntrs.nasa.gov/citations/19680011944>, NASA SP-147.

- Hayes, W. D., Haefeli, R. C., and Kulsrud, H. E. (1968). "Sonic Boom Propagation in a Stratified Atmosphere with Computer Program," NASA CR-1299, URL: <https://ntrs.nasa.gov/citations/19690013184>.
- Henderson, H. R., and Hilton, D. A. (1974a). "Sonic-boom ground pressure measurements from the launch and reentry of Apollo 16," NASA TN-D-7606, URL: <https://ntrs.nasa.gov/citations/19740023384>.
- Henderson, H. R., and Hilton, D. A. (1974b). "Sonic-boom measurements in the focus region during the ascent of Apollo 17," NASA TN-D-7806, URL: <https://ntrs.nasa.gov/citations/19750005520>.
- Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., De Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R. J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., de Rosnay, P., Rozum, I., Vamborg, F., Villaume, S., and Thépaut, J.-N. (2020). "The ERA5 global reanalysis," *Quarterly Journal of the Royal Meteorological Society* **146**(730), 1999–2049, DOI:10.1002/qj.3803, URL: <https://rmets.onlinelibrary.wiley.com/doi/abs/10.1002/qj.3803>.
- Hicks, R. M., and Mendoza, J. P. (1967). "Prediction of aircraft sonic boom characteristics from experimental near field results," NASA TM X-1477, URL: <https://ntrs.nasa.gov/citations/19680002304>.
- Hicks, R. M., and Mendoza, J. P. (1971a). "A Brief Study of the Space Shuttle Sonic Boom During Ascent," NASA TM X-62050, URL: Not Publicly Available.
- Hicks, R. M., and Mendoza, J. P. (1971b). "Wind Tunnel Pressure Signatures for a Delta Wing Space Shuttle Vehicle," NASA TM X-62040, URL: <https://ntrs.nasa.gov/citations/19710081724>.
- Hicks, R. M., and Mendoza, J. P. (1972). "Wind tunnel Pressure Signatures for a Delta Wing Space Shuttle Vehicle and a Space Shuttle Fuel Tank," NASA TM X-62030, URL: Not Publicly Available.
- Hicks, R. M., and Mendoza, J. P. (1973a). "An Investigation of the Feasibility of Simulating Gaseous Exhaust Plumes with Solid Bodies in Sonic Boom Studies," NASA TM X-62,131, URL: <https://ntrs.nasa.gov/citations/19790074159>.
- Hicks, R. M., and Mendoza, J. P. (1973b). "Pressure signatures for a .00053 scale model of the Saturn 5-Apollo launch vehicle with simulated exhaust plumes," NASA TM-X-62129, URL: <https://ntrs.nasa.gov/citations/19730022098>.
- Hicks, R. M., Mendoza, J. P., and Garcia, F. J. (1972a). "A Wind Tunnel Flight Correlation of Apollo 15 Sonic Boom," NASA TM X-62111, URL: <https://ntrs.nasa.gov/citations/19730004289>.

- Hicks, R. M., Mendoza, J. P., and Levy, L. L. J. (1971). "An Investigation of Sonic Boom for Straight- and Delta-Wing Space Shuttle Orbiters," NASA TM X-62030, URL: <https://ntrs.nasa.gov/citations/19710079289>.
- Hicks, R. M., Mendoza, J. P., and Levy, L. L. J. (1993). "Investigation of sonic boom for the Space Shuttle: High cross-range orbiter," NASA TM-108238, URL: <https://ntrs.nasa.gov/citations/19940026831>.
- Hicks, R. M., Mendoza, J. P., and Thomas, C. L. (1972b). "Pressure signatures for the Apollo command module and the Saturn 5 launch vehicle with a discussion of strong shock extrapolation procedures," NASA TM-X-62117, URL: <https://ntrs.nasa.gov/citations/19730005177>.
- Hilton, D. A., and Henderson, H. R. (1974). "Measurements of sonic-boom overpressures from Apollo space vehicles," J. Acoust. Soc. Am. **56**(2), 323–328, DOI:10.1121/1.1903261, URL: <https://doi.org/10.1121/1.1903261>.
- Hilton, D. A., Henderson, H. R., and McKinney, R. (1972). "Sonic-boom ground-pressure measurements from Apollo 15," NASA TN-D-6950, URL: <https://ntrs.nasa.gov/citations/19720023246>.
- Hilton, D. A., Huckel, V., and Maglieri, D. J. (1966). "Sonic-Boom Measurements During Bomber Training Operations in the Chicago Area," NASA TN D-3655, URL: <https://ntrs.nasa.gov/citations/19660029125>.
- Hilton, D. A., Huckel, V., Maglieri, D. J., and Steiner, R. (1964). "Sonic-boom exposures during faa community response studies over a 6-month period in the [O]klahoma [C]ity area," NASA TN D-2539, URL: <https://ntrs.nasa.gov/citations/19650002481>.
- Hilton, D. A., and Maglieri, D. J. (1966). "Experiments on the effects of atmospheric refraction and airplane accelerations on sonic-boom ground-pressure patterns," NASA TN D-3520, URL: <https://ntrs.nasa.gov/citations/19660021920>.
- Holloway, P. F., Wilhold, G. A., Jones, J. H., Garcia, F. J., and Hicks, R. M. (1973). "Shuttle sonic boom - Technology and predictions," DOI:10.2514/6.1973-1039, URL: <https://doi.org/10.2514/6.1973-1039>.
- Hu, W., Hickel, S., and van Oudheusden, B. W. (2022). "Unsteady mechanisms in shock wave and boundary layer interactions over a forward-facing step," J. Fluid Mech. **949**, A2, DOI:10.1017/jfm.2022.737, URL: <https://doi.org/10.1017/jfm.2022.737>.
- Hubbard, H. H. (1966). "Nature of the Sonic-Boom Problem," J. Acoust. Soc. Am. **39**(5B), S1–S9, DOI:10.1121/1.1914037, URL: <https://doi.org/10.1121/1.1914037>.
- Hubbard, H. H., Maglieri, D. J., Huckel, V., and Hilton, D. A. (1964). "Ground Measurements of Sonic-Boom Pressures for the Altitude Range of 10,000 to 75,000 feet," NASA TN D-2359, URL: <https://ntrs.nasa.gov/citations/19640014910>.

- ISO11204:2010 (2010). "Acoustics - Noise emitted by machinery and equipment Determination of emission sound pressure levels at a work station and at other specified positions applying accurate environmental corrections" URL: <https://www.iso.org/standard/54907.html>.
- James, M. M., Salton, A., Calton, M., Downing, J. M., Gee, K. L., and McInerny, S. A. (2020a). "Commercial Space Operations Noise and Sonic Boom Measurements," DOI:10.17226/25834, URL: <https://doi.org/10.17226/25834>.
- James, M. M., Salton, A. R., Calton, M. F., and Lympny, S. V. (2020b). "RUMBLE Launch Vehicle Noise and Emissions Simulation Model Version 3.0 User Guide," ACRP Report, Transportation Research Board, Washington, D. C., URL: <https://onlinepubs.trb.org/onlinepubs/acrp/acrp%5Fwod%5F051RumbleGuide.pdf>.
- Johnson, S. (2016). "From Double to Triple: Why the Landing Falcon 9 Creates Three Sonic Booms" URL: <https://www.spaceflightinsider.com/organizations/space-exploration-technologies/double-triple-landing-falcon-9-creates-three-sonic-booms/>, This is the original source for the quote. The website is not available for reasons unknown to the authors at the time of this publication, and a recent attempt to view the website resulted in a phishing warning from security software.
- Jung, T. P., Starkey, R. P., and Argrow, B. (2015). "Modified Linear Theory Sonic Booms Compared to Experimental and Numerical Results," J. Aircraft **52**(6), 1821–1837, DOI:10.2514/1.C033088, URL: <https://doi.org/10.2514/1.C033088>.
- Kellison, M. S., and Gee, K. L. (2023). "Sound power of NASA's lunar rockets: Space Launch System versus Saturn V," JASA Express Lett. **3**(11), 113601, DOI:10.1121/10.0022538, URL: <https://doi.org/10.1121/10.0022538>.
- Kellison, M. S., Gee, K. L., Cunningham, C. F., Coyle, W. L., Moore, T. R., and Hart, G. W. (2023). "Community-based noise measurements of the Artemis-I mission," Proc. Mtgs. Acoust. **51**(1), 040004, DOI:10.1121/2.0001786, URL: <https://doi.org/10.1121/2.0001786>.
- Kellison, M. S., Gee, K. L., Hall, L. K., Anderson, M. C., Moats, L. T., Perkins, M. T., Pulsipher, N. L., and Hart, G. W. (2025). "Falcon-9 ascent sonic boom measurements in Ventura County, California," J. Acoust. Soc. Am. **157**(4_Supplement), A62–A62, DOI:10.1121/10.0037394, URL: <https://doi.org/10.1121/10.0037394>.
- Kestin, J. (1950). "Influence of Variable Specific Heats on the High-Speed Flow of Air," C.P. No. 33 (13,176), URL: <https://naca.central.cranfield.ac.uk/bitstream/handle/1826.2/46/arc-cp-0033.pdf>.
- Klos, J. (2020). "Recommendations for Using Noise Monitors to Estimate Noise Exposure During X-59 Community Tests," NASA/TM-20205007926, URL: <https://ntrs.nasa.gov/citations/20205007926>.

- Klos, J. (2022). “An Adaptation of ISO 11204 using Customized Correction Grades to Mitigate Ambient Noise Effects when Computing Sonic Boom Loudness Levels,” NASA/TM-20220010779, URL: <https://ntrs.nasa.gov/citations/20220010779>.
- Klos, J. (2025). “Uncertainty Quantification for Empirical X-59 Sonic Boom Loudness Levels,” NASA TM-20250000107, URL: <https://ntrs.nasa.gov/citations/20250000107>.
- Klos, J., and Buehrle, R. D. (2007). “Vibro-Acoustic Response of Buildings Due to Sonic Boom Exposure: June 2006 Field Test,” NASA TM-214900, URL: <https://ntrs.nasa.gov/citations/20070031109>.
- Kramer, F. (1966). “Predicted acoustical performance of the S-1C SOUND suppressor,” NASA TN D-3398, URL: <https://ntrs.nasa.gov/citations/19660014564>.
- Krasnov, N. F. (1970). “Aerodynamics of Bodies of Revolution,” Report R-455-PR.
- Krider, E. P., Orville, R. E., Noggle, R. C., and Uman, M. A. (1974). “Lightning and the Apollo 17/Saturn V Exhaust Plume,” *Journal of Spacecraft and Rockets* **11**(2), 72–75, DOI:10.2514/3.62011, URL: <https://doi.org/10.2514/3.62011>.
- Landau, L. D., and Lifshitz, E. M. (1987). *Fluid Mechanics*, **6** of *Course of Theoretical Physics* (Elsevier), ISBN: 9780750627672.
- Langenais, A., Vuillot, F., Troyes, J., and Bailly, C. (2019). “Accurate simulation of the noise generated by a hot supersonic jet including turbulence tripping and nonlinear acoustic propagation,” *Physics of Fluids* **31**(1), 016105, DOI:10.1063/1.5050905, URL: <https://doi.org/10.1063/1.5050905>.
- Lee, J., Rathsam, J., and Wilson, A. (2020). “Bayesian statistical models for community annoyance survey data,” *J. Acoust. Soc. Am.* **147**(4), 2222–2234, DOI:10.1121/10.0001021, URL: <https://doi.org/10.1121/10.0001021>.
- Leishman, T. W., Rollins, S., and Smith, H. M. (2006). “An experimental evaluation of regular polyhedron loudspeakers as omnidirectional sources of sound,” *J. Acoust. Soc. Am.* **120**(3), 1411–1422, DOI:10.1121/1.2221552, URL: <https://doi.org/10.1121/1.2221552>.
- Levy, L. L. J., Hicks, R. M., and Mendoza, J. P. (1993). “Investigation of sonic boom for the Space Shuttle: Low cross-range orbiter,” NASA TM-108237, URL: <https://ntrs.nasa.gov/citations/19940026832>.
- Lighthill, M. J. (1948). “Supersonic flow past slender bodies of revolution the slope of whose meridian section is discontinuous,” *The Quarterly Journal of Mechanics and Applied Mathematics* **1**(1), 90–102, DOI:10.1093/qjmam/1.1.90, URL: <https://doi.org/10.1093/qjmam/1.1.90>.

- Lipkens, B., and Blackstock, D. T. (1998). "Model experiment to study sonic boom propagation through turbulence. Part I: General results," *J. Acoust. Soc. Am.* **103**(1), 148–158, DOI:10.1121/1.421114, URL: <https://doi.org/10.1121/1.421114>.
- Lonzaga, J. B. (2023). "Multiple scattering theory for modeling sonic booms in atmospheric turbulence," *J. Acoust. Soc. Am.* **154**(5), 3078–3088, DOI:10.1121/10.0022385, URL: <https://doi.org/10.1121/10.0022385>.
- Lonzaga, J. B., Page, J. A., Ahearn, M. J., Son, S. R., Downs, R. S., Loubeau, A., and Doebler, W. J. (2025). "PCBoom Version 7.5 User's Guide," NASA/TM-20250003188, URL: <https://ntrs.nasa.gov/citations/20250003188>.
- Lonzaga, J. B., Page, J. A., Downs, R. S., Kaye, S. R., Shumway, M. J., Loubeau, A., and Doebler, W. J. (2022). "PCBoom 7 Technical Reference," NASA/TM-20220007177, URL: <https://ntrs.nasa.gov/citations/20220007177>.
- Loubeau, A., and Doebler, W. (2019). "Comparison of sonic boom noise metrics from predictions and measurements under low atmospheric turbulence conditions," *J. Acoust. Soc. Am.* **145**(3_Supplement), 1899–1899, DOI:10.1121/1.5101886, URL: <https://doi.org/10.1121/1.5101886> (slides available at <https://ntrs.nasa.gov/citations/20200005310>).
- Loubeau, A., Naka, Y., Cook, B. G., Sparrow, V. W., and Morgenstern, J. M. (2015). "A new evaluation of noise metrics for sonic booms using existing data," *AIP Conference Proceedings* **1685**(1), 090015, DOI:10.1063/1.4934481, URL: <https://doi.org/10.1063/1.4934481>.
- Loubeau, A., and Page, J. (2018). "Human Perception of Sonic Boom from Supersonic Aircraft," *Acoustics Today* **14**(3), 23–30, URL: <https://acousticstoday.org/wp-content/uploads/2018/09/Human-Perception-of-Sonic-Booms-from-Supersonic-Aircraft-Alexandra-Loubeau.pdf>.
- Loubeau, A., Wilson, S. R., and Rathsam, J. (2018). "Updated evaluation of sonic boom noise metrics," *J. Acoust. Soc. Am.* **144**(3_Supplement), 1706–1706, DOI:10.1121/1.5067578, URL: <https://doi.org/10.1121/1.5067578>.
- Lubert, C. P. (2018). "From Sputnik to SpaceX: 60 Years of Rocket Launch Acoustics," *Acoustics Today* **14**, URL: <https://acousticstoday.org/from-sputnik-to-spacex-60-years-of-rocket-launch-acoustics-caroline-p-lubert/>.
- Lubert, C. P., Gee, K. L., and Tsutsumi, S. (2022). "Supersonic jet noise from launch vehicles: 50 years since NASA SP-8072," *J. Acoust. Soc. Am.* **151**(2), 752–791, DOI:10.1121/10.0009160, URL: <https://doi.org/10.1121/10.0009160>.
- Lympany, S. V., and Page, J. A. (2024). "The influence of atmospheric variability on predicted sonic boom metrics," Slides available from NASA Technical Reports Server: <https://ntrs.nasa.gov/citations/20240005397>, DOI:10.1121/10.0027413, URL: <https://doi.org/10.1121/10.0027413>.

- Lympany, S. V., Salton, A. R., and James, M. M. (2025). "Influence of atmospheric variability on sonic boom footprints from rocket launches,," J. Acoust. Soc. Am. **158**(4_supplement), A119, URL: <https://acousticalsociety.org/wp-content/uploads/2025/11/honolulu-programrevised1.pdf> DOI link not yet available.
- Lyrantzis, A. S., and Coderoni, M. (2020). "Overview of the Use of Large-Eddy Simulations in Jet Aeroacoustics," AIAA Journal **58**(4), 1620–1638, DOI:10.2514/1.J058498, URL: <https://doi.org/10.2514/1.J058498>.
- Maglieri, D. J., Bobbitt, P. J., Plotkin, K. J., Shepherd, K. P., Coen, P. G., and Richwine, D. M. (2014). "Sonic Boom: Six Decades of Research," NASA-SP-2014-622, URL: <https://ntrs.nasa.gov/citations/20150006843>.
- Maglieri, D. J., and Henderson, H. R. (1973). "Noise from aerial bursts of fireworks," J. Acoust. Soc. Am. **54**(5), 1224–1227, DOI:10.1121/1.1914370, URL: <https://doi.org/10.1121/1.1914370>.
- Maglieri, D. J., Henderson, H. R., Massey, S. J., and Stansbery, E. G. (2011). "A Compilation of Space Shuttle Sonic Boom Measurements," NASA/CR-2011-217080, URL: <https://ntrs.nasa.gov/citations/20110011322>.
- Maglieri, D. J., Hilton, D. A., and McLeod, N. J. (1966). "Further Experiments on the Effects of Atmospheric Refractions and Aircraft Accelerations on sonic Boom Ground Pressure Patterns," NASA TN D-3520, URL: Not Publicly Available.
- Maglieri, D. J., Huckel, V., and Henderson, H. R. (1972). "Sonic-boom measurements for SR-71 aircraft operating at Mach numbers to 3.0 and altitudes to 24384 meters," NASA TN D-6823, URL: <https://ntrs.nasa.gov/citations/19720023371>.
- Maglieri, D. J., and Sothcott, V. E. (1990). "Summary of Sonic Boom Rise Times Observed during FAA Community Response Studies over a 6-Month Period in the Oklahoma City Area," NASA-CR-4277, URL: <https://ntrs.nasa.gov/citations/19900015536>.
- Manhart, J. K., Ailman, C. M., Lane, S. R., and Marsh, A. H. (1966). "An Acoustical Study of the KIWI B Nuclear Rocket," NASA CR-370, URL: <https://ntrs.nasa.gov/citations/19660006206>.
- Marconi, F., Salas, M., and Yaeger, L. (1976). "Development of a computer code for calculating the steady super/hypersonic inviscid flow around real configurations. Volume 1: Computational technique," NASA CR-2675, URL: <https://ntrs.nasa.gov/citations/19760015406>.
- Marconi, F., and Yaeger, L. (1976). "Development of a computer code for calculating the steady super/hypersonic inviscid flow around real configurations. Volume 2: Code description," NASA CR-2676, URL: <https://ntrs.nasa.gov/citations/19760017064>.
- Marston, T. M. (2008). "Diffraction Correction and Low-frequency Response Extension for Condenser Microphones," Thesis, The Pennsylvania State University.

- Marwege, A., Hantz, C., Kirchheck, D., Klevanski, J., Gülhan, A., Charbonnier, D., and Vos, J. (2022). “Wind tunnel experiments of interstage segments used for aerodynamic control of retro-propulsion assisted landing vehicles,” *CEAS Space Journal* **14**, 447–471, DOI:10.1007/s12567-022-00425-4, URL: <https://doi.org/10.1007/s12567-022-00425-4>.
- Marwege, A., Riemer, J., Klevanski, J., Gülhan, A., Ecker, T., Reimann, B., and Dumont, E. (2019). “First Wind Tunnel Data of CALLISTO - Reusable VTVL Launcher First Stage Demonstrator,” DOI:10.13009/EUCASS2019-350, URL: <https://www.eucass.eu/doi/EUCASS2019-0350.pdf>.
- Mathews, L. T., Anderson, M. C., Gardner, C. D., McLaughlin, B. W., Hinds, B. M., McCullah-Boozer, M. R., Hall, L. K., and Gee, K. L. (2023). “An overview of acoustical measurements made of the Atlas V JPSS-2 rocket launch,” *Proc. Mtgs. Acoust.* **51**(1), 040003, DOI:10.1121/2.0001768, URL: <https://doi.org/10.1121/2.0001768>.
- Mathews, L. T., and Gee, K. L. (2025). “Methods for predicting overall sound power and maximum overall sound pressure levels from heated supersonic jets, including rockets,” *J. Acoust. Soc. Am.* **158**(1), 371–379, DOI:10.1121/10.0037192, URL: <https://doi.org/10.1121/10.0037192>.
- 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**(1), 620–633, DOI:10.1121/10.0005658, URL: <https://doi.org/10.1121/10.0005658>.
- Matoza, R. S., Fee, D., Neilsen, T. B., Gee, K. L., and Ogden, D. E. (2013). “Aeroacoustics of volcanic jets: Acoustic power estimation and jet velocity dependence,” *Journal of Geophysical Research: Solid Earth* **118**(12), 6269–6284, DOI:10.1002/2013JB010303, URL: <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2013JB010303>.
- McDonough, P. A. (1975). “Sonic boom results for a nominal mission 3B. Space Shuttle engineering and operations support, engineering systems analysis,” NASA CR-147769, URL: <https://ntrs.nasa.gov/citations/19760019112>.
- McDowell, J. (2026). “Master Orbital Launch Log” URL: <https://planet4589.org/space/gcat/data/derived/launchlog.html>, Last Viewed: 01-12-2026.
- McInerny, S. A. (1992). “Characteristics and predictions of far-field rocket noise,” *Noise Control Eng. J.* **38**(1), 5–16, DOI:10.3397/1.2827802, URL: <https://doi.org/10.3397/1.2827802>.
- McInerny, S. A. (1996). “Launch vehicle acoustics. I - Overall levels and spectral characteristics,” *Journal of Aircraft* **33**(3), 511–517, DOI:10.2514/3.46974, URL: <https://doi.org/10.2514/3.46974>.
- McInerny, S. A., and Ölçmen, S. M. (2005). “High-intensity rocket noise: Nonlinear propagation, atmospheric absorption, and characterization,” *J. Acoust. Soc. Am.* **117**(2), 578–591, DOI:10.1121/1.1841711, URL: <https://doi.org/10.1121/1.1841711>.
- McLean, F. E. (1965). “Some Nonasymptotic Effects on the Sonic Boom of Large Airplanes,” NASA TN-D-2877, URL: <https://ntrs.nasa.gov/citations/19650017049>.

- Mendoza, J. P. (1975a). "Sonic boom pressure signatures for the space shuttle launch vehicle," NASA TM X-62,441, URL: <https://ntrs.nasa.gov/citations/19750019956>.
- Mendoza, J. P. (1975b). "Wind tunnel pressure signatures for a 0.0041-scale model of the space shuttle orbiter," NASA TM X-62432, URL: <https://ntrs.nasa.gov/citations/19750017801>.
- Mendoza, J. P., and Hicks, R. M. (1971). "Wind tunnel pressure signatures for a .016 scale model of the Apollo command module," NASA TM X-62047, URL: <https://ntrs.nasa.gov/citations/19730005178>.
- Murugan, J. N., and Govardhan, R. N. (2016). "Shock wave-boundary layer interaction in supersonic flow over a forward-facing step," J. Fluid Mech. **807**, 258–302, DOI:10.1017/jfm.2016.574, URL: <https://doi.org/10.1017/jfm.2016.574>.
- Nagamatsu, H. T., Sheer, R. E., and Horvay, G. (1969). "Supersonic jet noise theory and experiments," NASA SP-207.
- Naka, Y. (2013). "Subjective evaluation of loudness of sonic booms indoors and outdoors," Acoust. Sci. & Tech. **34**(3), 225–228, DOI:10.1250/ast.34.225, URL: <https://doi.org/10.1250/ast.34.225>.
- NASA (1972). "Environmental Statement for the Space Shuttle Program, Final Statement," Not Publicly Available.
- NASA (1988). "Final (Tier 1) Environmental Impact Statement for the Galileo and Ulysses Missions," URL: <https://www.nasa.gov/wp-content/uploads/2018/04/hq-0019-hq-eis-galileo%5Fand%5Fulysses%5Fmissions-1988%5F0.pdf>.
- NASA (1989). "Final Environmental Impact Statement for the Galileo Mission (Tier 2)," URL: <https://www.nasa.gov/wp-content/uploads/2018/04/hq-0021-hq-eis-galileo%5Fmission%5Ftier%5F2%5F1989%5F0.pdf?emrc=1aadca>.
- NASA (1994). "Mars Pathfinder Mission Environmental Assessment," URL: <https://www.nasa.gov/wp-content/uploads/2018/04/mpf%5Ffea-7-1994%5F0.pdf?emrc=95af2d>.
- NASA (2014). "Final Environmental Impact Statement for the Mars 2020 Mission," URL: <https://www.nasa.gov/wp-content/uploads/2024/01/mars-2020-final-eis.pdf?emrc=2dfd52>.
- NASA (2026). "NASA Quesst Mission Webpage" URL: <https://www.nasa.gov/X59/>, Last Viewed: 04/09/2026.
- Niedzwiecki, A., and Ribner, H. S. (1978). "Subjective loudness of 'minimized' sonic boom waveforms," J. Acoust. Soc. Am. **64**(6), 1622–1626, DOI:10.1121/1.382127, URL: <https://doi.org/10.1121/1.382127>.
- Nixon, C. W., and Borsky, P. N. (1966). "Effects of Sonic Boom on People: St. Louis, Missouri, 1961-1962," J. Acoust. Soc. Am. **39**(5B), S51–S58, DOI:10.1121/1.1914044, URL: <https://doi.org/10.1121/1.1914044>.

- Nixon, C. W., and Hubbard, H. H. (1965). "Results of USAF-NASA-FAA flight program to study community responses to sonic booms in the greater St. Louis area," NASA TN D-2705, URL: <https://ntrs.nasa.gov/citations/19650014087>.
- NMFS, and NOAA (2013). "Taking and Importing Marine Mammals; Taking Marine Mammals Incidental to U.S. Air Force Launches, Aircraft and Helicopter Operations, and Harbor Activities Related To Launch Vehicles From Vandenberg Air Force Base (VAFB), California," CFR: 50 CFR 217. Document Citation: 78 FR 73794. Document Number: 2013-29203.
- NOAA (2019). "Taking and Importing Marine Mammals; Taking Marine Mammals Incidental to U.S. Air Force Launches and Operations at Vandenberg Air Force Base, California," CFR: 50 CFR 217. Document Citation: 84 FR 14314. Document Number: 2019-06918.
- NOAA, NASA, and ISAF (1976). "U.S. Standard Atmosphere, 1976," NOAA-S/T-76-1562, NASA-TM-X-74335, URL: <https://ntrs.nasa.gov/citations/19770009539>.
- Nyborg, K., Anderson, M. C., and Gee, K. L. (2024). "Turbulence-induced variability of a far-field Falcon-9 sonic boom measurement," J. Acoust. Soc. Am. **155**(3_Supplement), A256–A257, DOI:10.1121/10.0027414, URL: <https://doi.org/10.1121/10.0027414>.
- O'Farrell, J. M., and Rieckhoff, T. J. (2011). "Direct Visualization of Shock Waves in Supersonic Space Shuttle Flight," NASA TM-2011-216455, URL: <https://ntrs.nasa.gov/citations/20110007108>.
- OpenFOAM (2024). "OpenFOAM 11" URL: <https://www.openfoam.com>, Last viewed: 05-29-2025.
- Ortt, J. (2015). "A Comparison and Contrast of Environmental Monitoring Techniques from 2008 to 2014 on the Pacific Harbor Seal and Northern Channel Island Pinnipeds," Thesis, North Carolina State University, URL: <https://repository.lib.ncsu.edu/server/api/core/bitstreams/130f1d05-376c-4f9c-b650-f408a701527d/content>.
- Ozorowski, L. P., Shah, G. H., Coen, P. G., Loubeau, A., and Rathsam, J. (2021). "NASA Community Test Workshop 2," NASA Document ID: 20210025956, URL: <https://ntrs.nasa.gov/citations/20210025956>.
- Page, J., Plotkin, K. J., Hobbs, C., Sparrow, V., Salamone, J., Cowart, R., Salamone, J., Elmer, K., Welge, H. R., Ladd, J., Maglieri, D., and Piacsek, A. (2015). "Superboom Caustic Analysis and Measurement Program (SCAMP) Final Report," NASA/CR-2015-218871, URL: <https://ntrs.nasa.gov/citations/20150019419>.
- Page, J. A., Hodgdon, K. K., Hunte, R. P., Davis, D. E., Gaugler, T. A., Downs, R., Cowart, R. A., Maglieri, D. J., Hobbs, C., Baker, G., Collmar, M., Bradley, K. A., Sonak, B., Crom, D., and Cutler, C. (2020). "Quiet Supersonic Flights 2018 (QSF18) Test: Galveston, Texas Risk Reduction for Future Community Testing with a Low-Boom Flight Demonstration Vehicle," NASA/CR-2020-220589, URL: <https://ntrs.nasa.gov/citations/20200003224>.

- Page, J. A., Hodgdon, K. K., Kreckler, P., Cowart, R., Hobbs, C., Wilmer, C., Koenig, C., Holmes, T., Gaugler, T., Shumway, D. L., Rosenberger, J. L., and Philips, D. (2014). "Waveforms and Sonic Boom Perception and Response (WSPR) Low-Boom Community Response Program Pilot Test Design, Execution, and Analysis," NASA/CR-2014-218180, URL: <https://ntrs.nasa.gov/citations/20140002785>.
- Page, J. A., Lonzaga, J. B., Shumway, M. J., Son, S. R., Downs, R. S., Loubeau, A., and Doebler, W. J. (2023). "PCBoom 7.3 User's Guide," NASA/TM-20220016207, URL: <https://ntrs.nasa.gov/citations/20220016207>.
- Pedersen, K., Transtrum, M. K., Gee, K. L., Lympny, S. V., James, M. M., and Salton, A. R. (2021). "Validating two geospatial models of continental-scale environmental sound levels," JASA Express Lett. **1**(12), 122401, DOI:10.1121/10.0007368, URL: <https://doi.org/10.1121/10.0007368>.
- Pestorius, F. M. (1973). "Propagation of plane acoustic noise of finite amplitude," ARL-TR-73-23 (Applied Research Laboratories, The University of Texas at Austin, AD 778 868). This report is an adaptation of the Ph.D. dissertation by the same author (The University of Texas at Austin, 1973).
- Peters, C. E., and Phares, W. J. (1976). "An Approximate Analysis of the Shock Structure in Underexpanded Plumes," AEDC-TR-76-129, URL: <https://apps.dtic.mil/sti/tr/pdf/ADA030705.pdf>.
- Petitjean, B. P., Viswanathan, K., and McLaughlin, D. K. (2006). "Acoustic Pressure Waveforms Measured in High Speed Jet Noise Experiencing Nonlinear Propagation," International Journal of Aeroacoustics **5**(2), 193–215, DOI:10.1260/14754720677629835, URL: <https://doi.org/10.1260/14754720677629835>.
- Plotkin, K., and Cantril, J. (1976). "Prediction of sonic boom at a focus," DOI:10.2514/6.1976-2, URL: <https://doi.org/10.2514/6.1976-2>.
- Plotkin, K. J., Franz, R. J., and Haering, Edward A., J. (2006a). "Prediction and measurement of a weak sonic boom from an entry vehicle," J. Acoust. Soc. Am. **120**(5_Supplement), 3077–3077, DOI:10.1121/1.4787408, URL: <https://doi.org/10.1121/1.4787408>.
- Plotkin, K. J., Haering, Edward A., J., and Murray, J. E. (2006b). "Low-Amplitude Sonic Boom From a Descending Sounding Rocket," AIP Conference Proceedings **838**(1), 615–618, DOI:10.1063/1.2210428, URL: <https://doi.org/10.1063/1.2210428>.
- Potter, A. (1983). "Environmental effects of Shuttle launch and landing," DOI:10.2514/6.1983-2577, URL: <https://doi.org/10.2514/6.1983-2577>.
- Raje, P., Saikia, B., and Sinha, K. (2017). "Numerical investigation of axisymmetric underexpanded supersonic jets," Proceedings of the 1st National Aerospace Propulsion Conference, IIT Kanpur, Kanpur URL: https://www.hypersonic-cfd.com/Inhouse_papers/2017/NAPC_Pratik.pdf nAPC-2017-139.

- Rallabhandi, S. K. (2011). "Advanced Sonic Boom Prediction Using the Augmented Burgers Equation," *Journal of Aircraft* **48**(4), 1245–1253, DOI:10.2514/1.C031248, URL: <https://doi.org/10.2514/1.C031248>.
- Rallabhandi, S. K., and Loubeau, A. (2022). "Summary of Propagation Cases of the Third AIAA Sonic Boom Prediction Workshop," *Journal of Aircraft* **59**(3), 578–594, DOI:10.2514/1.C036327, URL: <https://doi.org/10.2514/1.C036327>.
- Rasband, R. D., Gee, K. L., Gabrielson, T. B., and Loubeau, A. (2023). "Improving low-frequency response of sonic boom measurements through digital filtering," *JASA Express Lett.* **3**(1), 014802, DOI:10.1121/10.0016751, URL: <https://doi.org/10.1121/10.0016751>.
- Rathsam, J. (2022). "An Overview of NASA's Low Boom Flight Demonstration," NASA Document ID: 20220005452, URL: <https://ntrs.nasa.gov/citations/20220005452>.
- Ribner, H. S., and Roy, D. (1982). "Acoustics of thunder: A quasilinear model for tortuous lightning," *J. Acoust. Soc. Am.* **72**(6), 1911–1925, DOI:10.1121/1.388621, URL: <https://doi.org/10.1121/1.388621>.
- Ritzel, D. V., and Gottlieb, J. J. (1987). "The Overpressure Signature from a Supersonic Projectile," UTIAS Report No. 279, URL: <https://resolver.tudelft.nl/uuid:734ac0e0-8ab6-43a7-9d3f-dc65bc9a5c5e>.
- Roberts, C., W., J., Herbert, G., and Hass, W. A. (1967). "Meteorological Investigations. National Sonic Boom Evaluation Office: Sonic Boom Experiments at Edwards Air Force Base, NSBEO-1-67," (Contract AF 49 (638), 1758), Stanford Research Inst., July 28, 1967, Part 1, Annex D. DD-D-1 through D-11 (also A-10 and A-14), URL: <https://apps.dtic.mil/sti/tr/pdf/AD0655310.pdf>.
- Saha, S., Moorthi, S., Wu, X., Wang, J., Nadiga, S., Tripp, P., Behringer, D., Hou, Y.-T., ya Chuang, H., Iredell, M., Ek, M., Meng, J., Yang, R., Mendez, M. P., van den Dool, H., Zhang, Q., Wang, W., Chen, M., and Becker, E. (2014). "The NCEP Climate Forecast System Version 2," *Journal of Climate* **27**(6), 2185–2208, DOI:10.1175/JCLI-D-12-00823.1, URL: <https://doi.org/10.1175/JCLI-D-12-00823.1>.
- Salamone, J., Sparrow, V., and Cowart, R. (2013). "SCAMP: Solution of the Lossy Nonlinear Tricomi Equation for Sonic Boom Focusing," DOI:10.2514/6.2013-935, URL: <https://doi.org/10.2514/6.2013-935>.
- Schomer, P. D. (2004). "Some important factors in community response to sonic booms," *INTER-NOISE and NOISE-CON Congress and Conference Proceedings* **2004**(1), 551–556, URL: <https://ince.publisher.ingentaconnect.com/content/ince/incecp/2004/00002004/00000001/art00066>.
- Shepherd, K. P., and Sullivan, B. M. (1991). "A Loudness Calculation Procedure Applied to Shaped Sonic Booms," NASA TP-3134, URL: <https://ntrs.nasa.gov/citations/19920002547>.

- Sheskin, D. J. (2000). *Handbook of Parametric and Nonparametric Statistical Procedures* (CRC Press), 2nd Edition. ISBN: 158488133X.
- Shrout, B. L., Mack, R. J., and Dollyhigh, S. M. (1971). "A wind-tunnel investigation of sonic-boom pressure distributions of bodies of revolution at Mach 2.96, 3.83, and 4.63," NASA TN D-6195, URL: <https://ntrs.nasa.gov/citations/19710012486>.
- SimScale (2025). "K-Omega Turbulence Models" URL: <https://www.simscale.com/docs/simulation-setup/global-settings/k-omega-sst/>, Last Viewed: 04-21-2025.
- SpaceX (2023). "Transporter-8 Mission" URL: <https://www.youtube.com/watch?v=zO3luySkHQU&t=853s>, Last viewed: 05-29-2025.
- SpaceX (2026). "Falcon 9: First Orbital Class Rocket Capable of Reflight" URL: <https://www.spacex.com/vehicles/falcon-9/>, Last viewed: 02-13-2025.
- Stanley, J. F. (2005). "Sonic boom measurement for space shuttle," J. Acoust. Soc. Am. **76**(S1), S53–S53, DOI:10.1121/1.2021906, URL: <https://doi.org/10.1121/1.2021906>.
- Stanley Creative (2023). "Falcon 9 - SpaceX" URL: <https://sketchfab.com/3d-models/falcon-9-spacex-394f7cf52d124bbd9db69f24d1ff2f08>, last Viewed: 04-09-2026.
- Stansbery, E. G. (1985). "An Experimental Investigation of the Space Shuttle Sonic Boom," Thesis, University of Houston, URL: <https://uh-ir.tdl.org/items/218c9639-d907-4a06-a6a3-12e9f25bbb41/full>.
- Stansbery, E. G., and Stanley, J. F. (1984). "Sonic Boom Levels Measured for STS-41-D Launch," NASA JSC-20218, URL: Not Publicly Available.
- Stansbery, E. G., Stanley, J. F., and Potter, A. E. (1983). "Sonic Boom Levels Measured for STS-7 Launch," NASA JSC-19237, URL: Not Publicly Available.
- Stevens, S. S. (1972). "Perceived Level of Noise by Mark VII and Decibels (E)," J. Acoust. Soc. Am. **51**(2B), 575–601, DOI:10.1121/1.1912880, URL: <https://doi.org/10.1121/1.1912880>.
- Stewart, B. S. (1993). "Behavioral and hearing responses of pinnipeds to rocket launch noise and sonic boom," J. Acoust. Soc. Am. **94**(3_Supplement), 1828–1828, DOI:10.1121/1.407787, URL: <https://doi.org/10.1121/1.407787>.
- Stout, T. A. (2018). "Simulation of N-Wave and Shaped Supersonic Signature Turbulent Variations," Dissertation, The Pennsylvania State University, URL: <https://etda.libraries.psu.edu/catalog/15959tqs5346>.
- Stout, T. A., and Sparrow, V. W. (2018). "Nonlinear propagation of shaped supersonic signatures through turbulence," Proc. Mtgs. Acoust. **34**(1), 045011, DOI:10.1121/2.0000872, URL: <https://doi.org/10.1121/2.0000872>.

- Stout, T. A., and Sparrow, V. W. (2019). “Three-dimensional Simulation of Shaped Sonic Boom Signature Loudness Variations Due to Atmospheric Turbulence,” DOI:10.2514/6.2019-2562, URL: <https://doi.org/10.2514/6.2019-2562>.
- Stout, T. A., and Sparrow, V. W. (2022). “Atmospheric turbulence effects on shaped and unshaped sonic boom signatures,” J. Acoust. Soc. Am. **151**(5), 3280–3290, DOI:10.1121/10.0011393, URL: <https://doi.org/10.1121/10.0011393>.
- Stout, T. A., Sparrow, V. W., and Blanc-Benon, P. (2021). “Evaluation of numerical predictions of sonic boom level variability due to atmospheric turbulence,” J. Acoust. Soc. Am. **149**(5), 3250–3260, DOI:10.1121/10.0004985, URL: <https://doi.org/10.1121/10.0004985>.
- Sutton, G. P., and Biblarz, O. (2017). *Rocket Propulsion Elements* (Wiley, New York), 9th Edition.
- Tam, C. K. W. (1972). “On the noise of a nearly ideally expanded supersonic jet,” J. Fluid Mech. **51**(1), 69–95, DOI:10.1017/S0022112072001089, URL: <https://doi.org/10.1017/S0022112072001089>.
- Tasissa, A. F., Hautefeuille, M., Fitek, J. H., and Radovitzky, R. A. (2016). “On the formation of Friedlander waves in a compressed-gas-driven shock tube,” Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences **472**(2186), 20150611, DOI:10.1098/rspa.2015.0611, URL: <https://doi.org/10.1098/rspa.2015.0611>.
- Taylor, A. D. (1980). “The TRAPS Sonic Boom Program,” ERL ARL-87, URL: https://www.arl.noaa.gov/wp_arl/wp-content/uploads/2017/08/arl-87.pdf.
- The MathWorks, Inc. (2022). “MATLAB r2022a” .
- Thomas, C. L. (1971). “Extrapolation of Wind Tunnel Sonic Boom Signatures Without Use of a Whitham F-function,” NASA SP-255, URL: <https://ntrs.nasa.gov/citations/19710018902>.
- Thomas, C. L. (1972). “Extrapolation of Sonic Boom Pressure Signatures by the Waveform Parameter Method,” NASA TN D-6832, URL: <https://ntrs.nasa.gov/citations/19720018354>.
- Tiegerman, B. (1975). “Sonic Booms from Drag Dominated Hypersonic Vehicles,” Thesis, Cornell University, URL: <https://www.proquest.com/dissertations-theses/sonic-booms-drag-dominated-hypersonic-vehicles/docview/302770181/se-2>, Available from ProQuest Dissertations & Theses Global. (302770181).
- USAF (1990). “Environmental Assessment Titan IV/Solid Rocket Motor Upgrade Program,” URL: <https://natspublic.grc.nasa.gov/main/Titan%20IV%20SRM%20Upgrade%20Program%20USAF%20EIA%20CCAFS-VAFB-2-1990.pdf>.
- USAF (2018). “Application for Incidental Take Regulations and Letters of Authorization; U.S. Air Force Launches, Aircraft and Helicopter Operations at Vandenberg Air Force Base, California,” URL: <https://media.fisheries.noaa.gov/dam-migration/vandenberg%5F2019loa%5Fapp2%5Fopr1.pdf>.

- USSF (2022). "Taking Marine Mammals Incidental to Space Vehicle and Missile Launches and Aircraft Test Flight and Helicopter Operations at Vandenberg Air Force Base, California," URL: <https://www.fisheries.noaa.gov/s3/2024-01/Vandenberg-2019LOA-MonRep2022-OPR1.pdf>.
- USSF (2023). "Taking Marine Mammals Incidental to Space Vehicle and Missile Launches and Aircraft Test Flight and Helicopter Operations at Vandenberg Air Force Base, California," URL: <https://www.fisheries.noaa.gov/s3/2024-03/VandenbergSFB-2019LOA-MonRep2023-OPR1.pdf>.
- Vaisala (2017). "Vaisala Radiosonde RS41-SGP" URL: <https://docs.vaisala.com/v/u/B211321EN-L/en-US>, Hardware Specification Sheet. Last Viewed: 01-21-2026.
- Viswanath, K., Brentner, K. S., Gimelshein, S. F., and Levin, D. A. (2005). "Investigation of Soot Combustion in Underexpanded Jet Plume Flows," *Journal of Thermophysics and Heat Transfer* **19**(3), 282–293, DOI:10.2514/1.12956, URL: <https://doi.org/10.2514/1.12956>.
- Wade, M. (2025). "RD-180" URL: <https://www.astronautix.com/r/rd-180.html>, Last Viewed: 09-04-2025.
- Walkden, F. (1958). "The Shock Pattern of a Wing-Body Combination, Far from the Flight Path," *Aeronautical Quarterly* **9**(2), 164–194, DOI:10.1017/S0001925900001372, URL: <https://doi.org/10.1017/S0001925900001372>.
- Whitham, G. B. (1952). "The flow pattern of a supersonic projectile," *Communications on Pure and Applied Mathematics* **5**(3), 301–348, DOI:10.1002/cpa.3160050305, URL: <https://doi.org/10.1002/cpa.3160050305>.
- Wilson, D. K. (2000). "A turbulence spectral model for sound propagation in the atmosphere that incorporates shear and buoyancy forcings," *J. Acoust. Soc. Am.* **108**(5), 2021–2038, DOI:10.1121/1.1311779, URL: <https://doi.org/10.1121/1.1311779>.
- Wooten, R. C., and Potter, A. E. (1983). "Shuttle-focused Sonic Boom: The Need for Direct Evidence," *Space Shuttle Environmental Effects: The First 5 Flights*. NASA CR-171812 JSC-19091, URL: <https://ntrs.nasa.gov/citations/19850002149>.
- Zepler, E., and Harel, J. (1965). "The loudness of sonic booms and other impulsive sounds," *Journal of Sound and Vibration* **2**(3), 249–256, DOI:10.1016/0022-460X(65)90111-2, URL: [https://doi.org/10.1016/0022-460X\(65\)90111-2](https://doi.org/10.1016/0022-460X(65)90111-2).
- Zhou, Z., Wang, X., Lu, C., and Le, G. (2020). "Numerical analysis on thermal environment of liquid rocket with afterburning under different altitudes," *Applied Thermal Engineering* **178**, 115584, DOI:10.1016/j.applthermaleng.2020.115584, URL: <https://www.sciencedirect.com/science/article/pii/S1359431120330660>.