Department of Defense Noise Working Group (DNWG)

Technical Bulletin

Sonic Boom

SUMMARY

This technical bulletin offers advice on how to address sonic boom noise, both qualitatively and quantitatively, in relation to noise exposure from military training and testing operations. The intent is to help program officials access useful technical information, respond to and educate the public, and incorporate this information as part of a compatible use and/or environmental assessment process.

INTRODUCTION

Sonic Boom is one of a series of technical bulletins issued by the DOD Noise Working Group (DNWG) under the initiative to educate and train DOD military, civilian, and contractor personnel as well as the general public on military noise issues (DOD 2006). A better understanding of military noise exposure by military personnel, local officials, other stakeholders, and the public may reduce and, possibly, over time, minimize encroachment on installations by non-compatible noise sensitive development.

This technical bulletin offers advice on how to address sonic boom noise, both qualitatively and quantitatively, in relation to noise exposure from military training and testing operations. The intent is to help program officials access useful technical information, respond to and educate the public, and incorporate this information as part of a compatible use and/or environmental assessment process.

This technical bulletin was last updated March 2024. The DNWG conducted a literature review on the enclosed content and determined that the current body of research still represents the best available science on the subject.

BACKGROUND

A. What Is a Sonic Boom?

A sonic boom is an impulsive noise like the initial crack of thunder (*i.e., thunder minus the rumble*). It is caused by an object moving faster than the speed of sound — about 750 miles per hour at sea level. An aircraft traveling through the atmosphere continuously produces pressure waves like bow waves caused by a ship. When the aircraft exceeds the speed of sound, these pressure waves merge and form shock waves that may be perceived as audible booms.

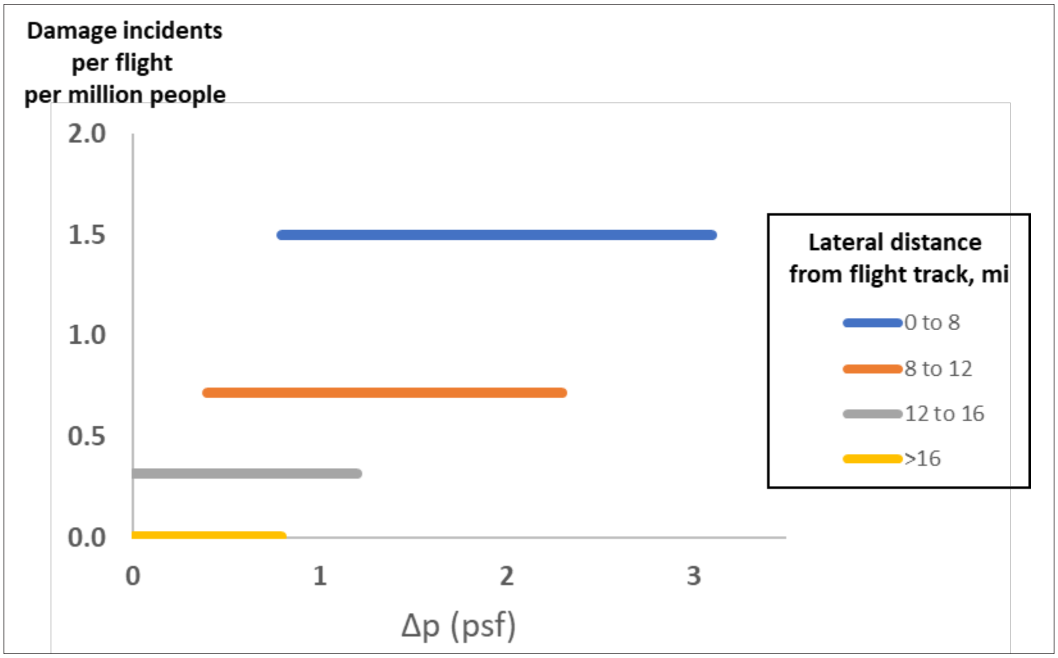
What we describe as a sonic boom, as heard on the ground, is the sudden onset and release of the pressure buildup in the shock waves. The change, or peak, in pressure caused by sonic booms is only a few pounds per square foot (psf), whereas absolute atmospheric pressure at sea level is 2,117 psf. The change in pressure experienced from a typical sonic boom is about the same pressure change experienced on an elevator as it descends two or three floors; the difference is that the pressure change occurs over a significantly shorter period for sonic booms. The magnitude of this peak pressure change is the basic description of the intensity of sonic booms.

B. Context

A major concern early in the history of sonic boom investigation was the effects they might have on other aircraft. Investigators (*Jordan et al., 1957*; *Maglieri and Morris, 1963*) found minimal expected effects of sonic booms, except for supersonic flights within small distances (*hundreds of feet*) of other aircraft. With the establishment of the Supersonic Transport (SST) program, research then shifted to the effects on communities in anticipation of supersonic transport aircraft flying across the continental United States on a regular basis. During this period, three extensive community overflight investigations were conducted: St. Louis (*1961–1962*), Oklahoma City (*1964*), and Chicago (*1965*).

The St. Louis overflight investigation did not include any instrumented test structures. Researchers used the lodged complaints to compile all of the property damage data (*Clark et al., 1965*). From this study, the researchers developed an engineering evaluation on the received damage claims during the study. The researchers determined that only 20% were from sonic booms (*Nixon and Hubbard, 1965*). Figure 1 provides a breakdown of the rate of sonic boom incidents for different exposure groups with peak overpressure represented by the x-axis and the rate of incidents is the y-axis. The groups were divided by their distance to the flight track. As expected, the groups closest to the flight track were exposed to the highest range of sonic boom levels and experienced the highest rate of damage incidents. The incident rates decreased with decreasing boom levels.

Figure 1 Sonic Boom-induced Damage Incidents for the St. Louis Overflight Study (*adapted from Hubbard & Mayes, 1967*)



The Oklahoma City overflight investigation included six months of supersonic overflights (*eight passes per day*) with a planned range of sonic boom overpressures of 1.5 to 2.0 psf. This study included measurements of sonic booms (*Hilton, Huckel, Steiner, and Maglieri, 1964*), an extensive set of measurements of structural response to sonic booms (*Andrews et al., 1965*), and community response surveys and interviews (*Borsky, 1965*). During the six-month test, 4,629 damage claims were filed, and 15,116 formal complaints were received. The sonic boom measurements demonstrated the variability of sonic boom overpressures where the distribution of the overpressures was between 50% to 200% of the predicted value. The structural response and sonic boom measurements allow the development of correlations to boom levels and potential damage (*Wiggins, 1965*). From the damage observations, no evidence of cumulative damage was found; glass breakage was caused by stress raisers combined with sonic boom impacts and plaster damage was spalling of old cracks, hairline extensions of existing cracks, and falling plaster. The results of the social surveys and interviews state that a majority of the public could learn to accept the sonic boom levels they were exposed to. However, the study found that annoyance increased during the study and that the community annoyance at the end of the study ranged from 25% to 76% depending on the subgroup.[1]

1 *The Oklahoma City Sonic Boom Study was conducted without informed consent.*

Following these overflight investigations, additional testing took place at the White Sands Missile Range (WSMR) (*1965*), a region near Las Vegas (*1966*), and Edwards Air Force Base (AFB) (*1967*). The WSMR tests included overpressures in the range of 1 to 38 psf. These tests included 21 carefully instrumented structures to characterize the sonic booms generated and the effects on the structures (*John A. Blume and Associates Research Division, 1965*). The Las Vegas area tests were low altitude, very high overpressure (*20–100 psf*) tests that produced information on window breakage from sonic booms (*Maglieri et al., 1966*). These series of tests culminated in the low overpressure tests at Edwards AFB that involved a range of U.S. Air Force aircraft, enabling the researchers to relate aircraft characteristics to structural response (*Blume et al., 1967*). With the cancellation of the SST program and with the restriction of the Concorde to transoceanic supersonic flight, major research programs in sonic boom effects disappeared.

DOD has conducted faster-than-sound test flights since 1947, and today most fighter aircraft are capable of supersonic speeds. Consequently, supersonic training flights that simulate actual combat conditions are necessary to ensure the success and survival of aircrews during wartime. However, DOD requires that flights be over open water above 10,000 feet and no closer than 15 miles from shore, whenever possible. Supersonic operations over land must be conducted above 30,000 feet or, for operations below 30,000 feet, in specially designated airspaces approved by DOD and the Federal Aviation Administration (FAA). These overland special-use airspaces generally have very low populations under them.

Supersonic flight operations for military aircraft generally involve short segments with some maneuvering. For fourth-generation fighter aircraft, such as the F-16 and F/A-18, supersonic flight segments vary from 20 seconds to two minutes. For fifth-generation fighter aircraft (*e.g., F-22, F-35*), supersonic segments can be longer than 10 minutes for certain training operations. Flight maneuvers, including accelerating, diving, and turning, can focus the boom (*U-waves*). For these focused sonic booms, the area of exposure is approximately hundreds of square feet. Other maneuvers such as deceleration and climbing can reduce the strength of the boom. In some instances, weather conditions can focus or distort sonic booms.

Sonic booms produced by DOD flight operations are heard primarily by people living in low population areas in the vicinity of certain Special Use Airspace (SUA). Sonic booms are generally experienced at random and relatively infrequent times within these areas as short duration noise intrusions of widely varying level. DOD considers that longterm annoyance produced by such exposure is the most salient effect of supersonic operations (*Galloway, 1983*). Predictions of longterm community annoyance to sonic booms use averages of outdoor exposure levels and the number of boom events over a period of a month or longer.

A relatively new factor is space travel. The recent increase in launch events from commercial space carriers creates a new source of sonic booms. The U.S. Space Force predicts a future increase in launch tempos to enable expanding space domain defense infrastructures. Booms emitted from launches and often landings (*i.e., reusable rocket stages and passengers/cargo transport*) travel down to the surface of the earth. The acceleration to escape velocity and the reentry velocity both create sonic booms for areas under the flight path. U.S. military strategies include an increase in the number and frequency of defense-related satellites launched into space.

C. Sonic Boom Characteristics

We define noise as sound that interferes with normal activities or the natural environment, and most sonic booms fall into this category. Three principal physical characteristics are involved in the measurement and human perception of sound: intensity, frequency, and duration.

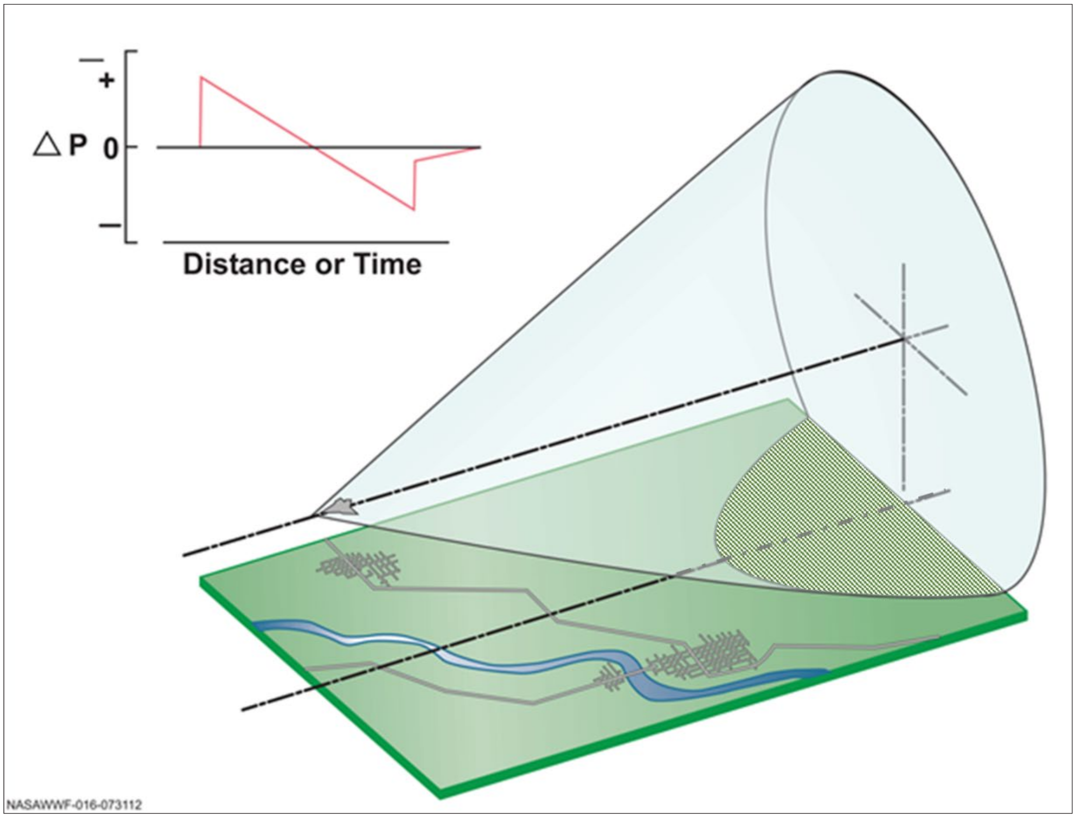
- **Intensity** is a measure of a sound's acoustic energy and is related to sound pressure. The greater the sound pressure, the more energy is carried by the sound and the louder the perception of that sound.
- **Frequency** is the oscillations of pressure waves that can be heard. Frequency is measured in terms of cycles per second or hertz (Hz). Human hearing ranges in frequency from 20 to 20,000 Hz.
- **Duration** is the length of time of the sonic boom.

Sonic boom intensity is quantified with physical pressure units rather than levels as with other noise sources. Sonic boom intensities are traditionally described by the amplitude of the front shock wave, referred to as the "peak overpressure" as noted in Figure 2. The peak overpressure is normally described in psf units, where 1 psf = 47.88 Pascals (Pa). The amplitude is particularly relevant when assessing structural effects, as opposed to loudness or cumulative community response.

The energy from sonic booms is concentrated in the 0.1 to 100 Hz frequency range, which is considerably below that of subsonic aircraft, gunfire, and most industrial noise. The duration of sonic booms is brief: 100 to 200 milliseconds (*0.1 to 0.2 seconds*) for most fighter aircraft and 500 milliseconds (*0.5 seconds*) for spacecraft.

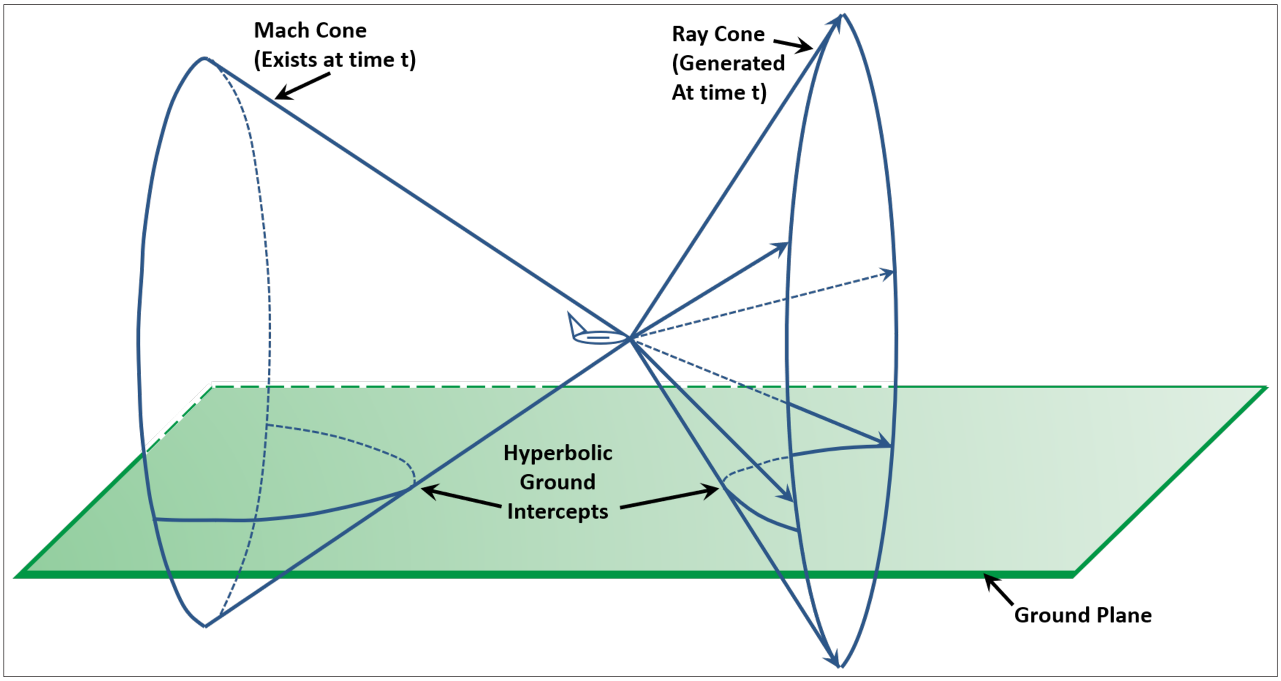
The intensity and width of a sonic boom exposure depends on the physical characteristics of the aircraft and how the aircraft is operating. In general, the higher the aircraft's altitude, the lower the overpressure on the ground. Higher altitude also widens the area of exposure on the ground to sonic booms. Overpressures across the ground are not the same in intensity. The boom will be greatest directly under the flight path and then progressively decrease with the horizontal distance away from the aircraft's flight track. A general rule of thumb is that the ground width of the sonic boom exposure area is approximately one mile for every 1,000 feet of altitude. Thus, an aircraft flying supersonic at 30,000 feet will create a boom with a ground width of about 30 miles at sea level, although the overpressures across the ground will be much less relative to an aircraft flying lower. For steady supersonic flight, the sonic boom wave form is characterized by two shocks that are separated by a linear pressure decompression. This steady sonic boom is described as a “carpet boom” since the boom rolls along with the aircraft as the aircraft maintains steady supersonic flight (*see Figure 2*). This type of flight will expose a large area to sonic booms — an area approximating hundreds of square miles as the aircraft continues to generate sonic booms at each point along its flight. However, these types of supersonic flights are rare for military aircraft.

Figure 2 Sonic Boom Carpet for a Vehicle in Steady Flight



A common misconception is that sonic booms are swept backward from the aircraft and always hit the ground behind the aircraft. An analogy that helps to describe the propagation of sonic booms is to imagine dropping objects from a moving vehicle. As an aircraft flies at supersonic speeds, it is continually generating shock waves — “dropping” sonic booms along its flight path. Once released, the sonic boom travels forward from the “release” (*or generation*) point (*see Figure 3*). From the perspective of the aircraft in steady level flight, the boom appears to be swept backwards as it travels away from the aircraft. However, if a supersonic aircraft performs a sharp turn or pulls upward, the boom will hit the ground in front of the aircraft.

Figure 3 Mach Cone Versus Ray Cone Viewpoints



D. Sonic Boom Waveforms

There are two basic types of sonic booms: N-waves and U-waves (*see Figure 4*). The N-wave is generated from steady flight conditions (*i.e., constant airspeed and direction as shown in Figure 2*); its pressure wave is shaped like the letter "N." N-waves have a front, positive pressure shock, which is followed by a linear (*steady*) decrease in the pressure until the rear shock returns the pressure back to the ambient pressure condition. The U-wave, or focused boom, is generated from non-steady maneuvering flights (*see Figure 5*), and its pressure wave is shaped like a "U." U-waves have positive pressure shocks at the front and rear of the boom, such that the peak pressures are increased compared to the N-wave. For today's military supersonic aircraft in normal operating conditions, the peak additional pressure (*or "overpressure"*) varies from less than 1 to about 10 psf for an N-wave type boom. Peak overpressure for U-waves is amplified two to five times the N-wave peak overpressure but only impacts a very small area when compared to the area exposed to the rest of the sonic boom footprint.

Figure 4 Sonic Boom Waveforms:
Carpet Boom ("N-wave") and Focused Boom ("U-wave")

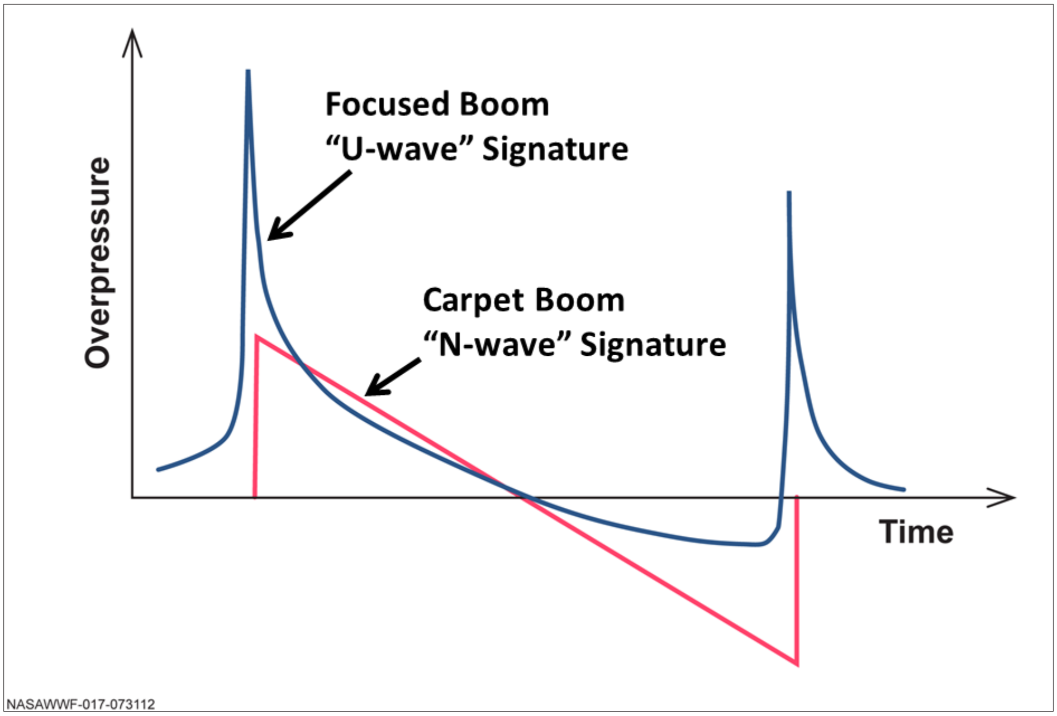


Figure 5 Sonic Boom Focus due to Level Acceleration

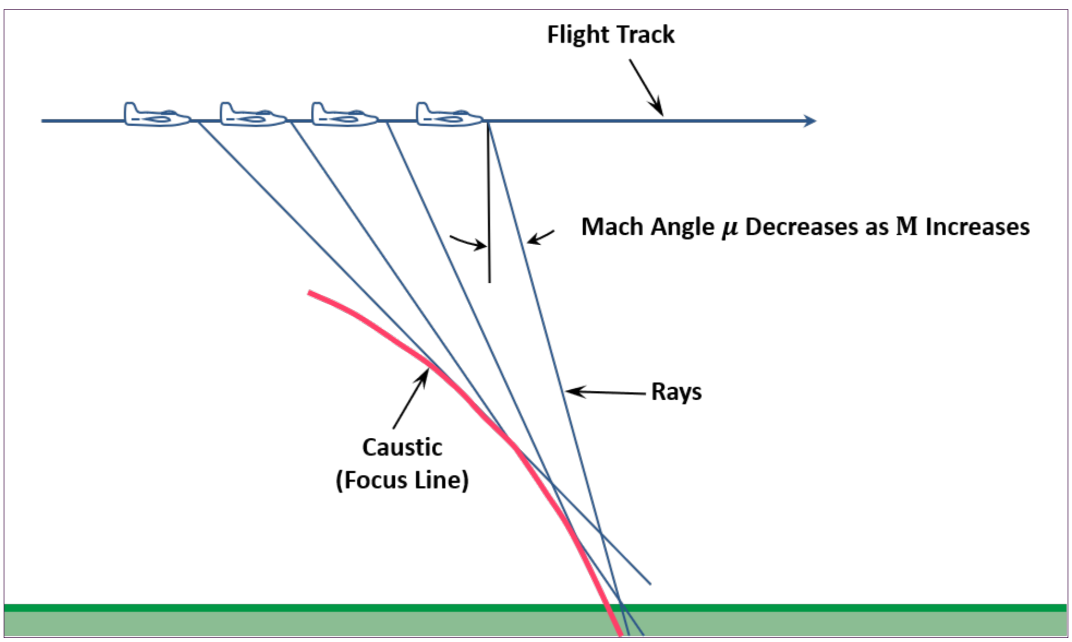
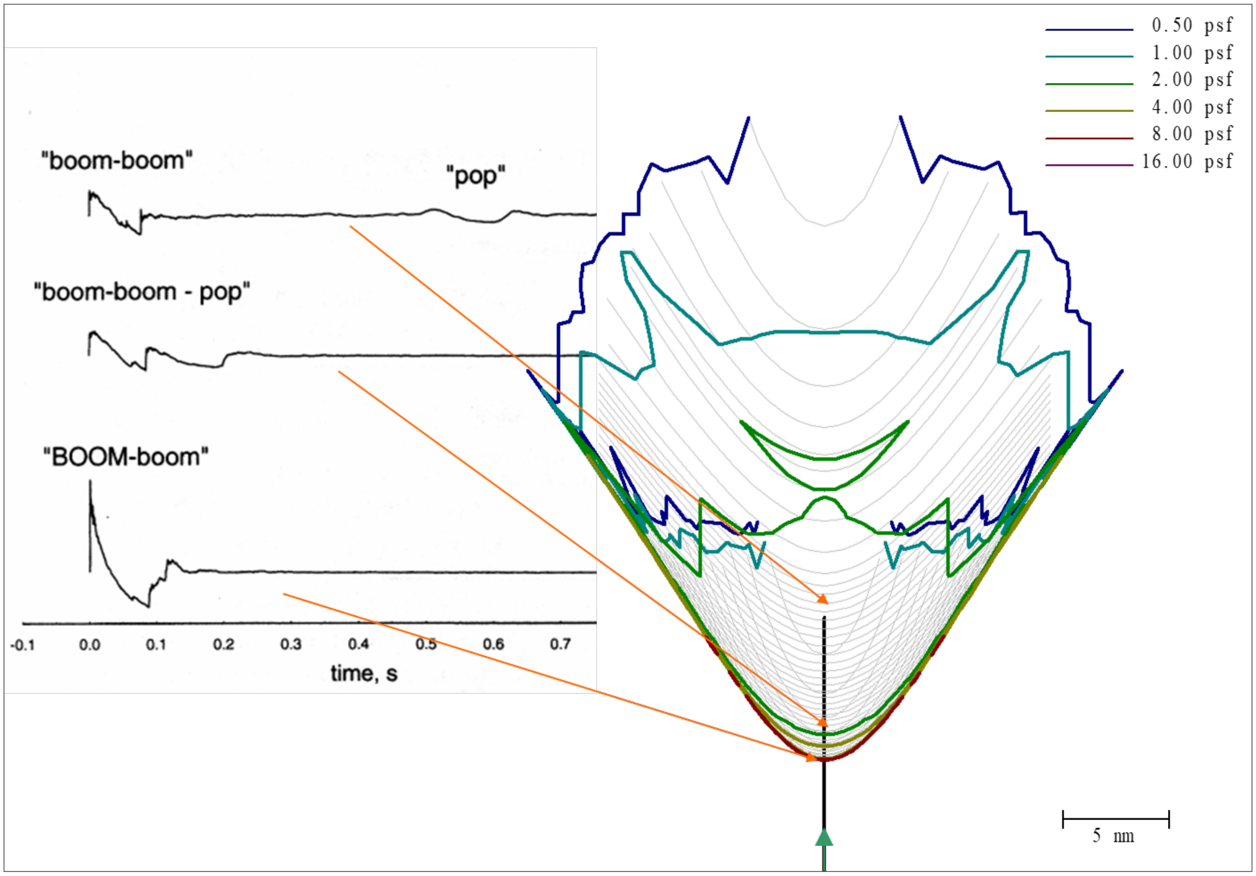


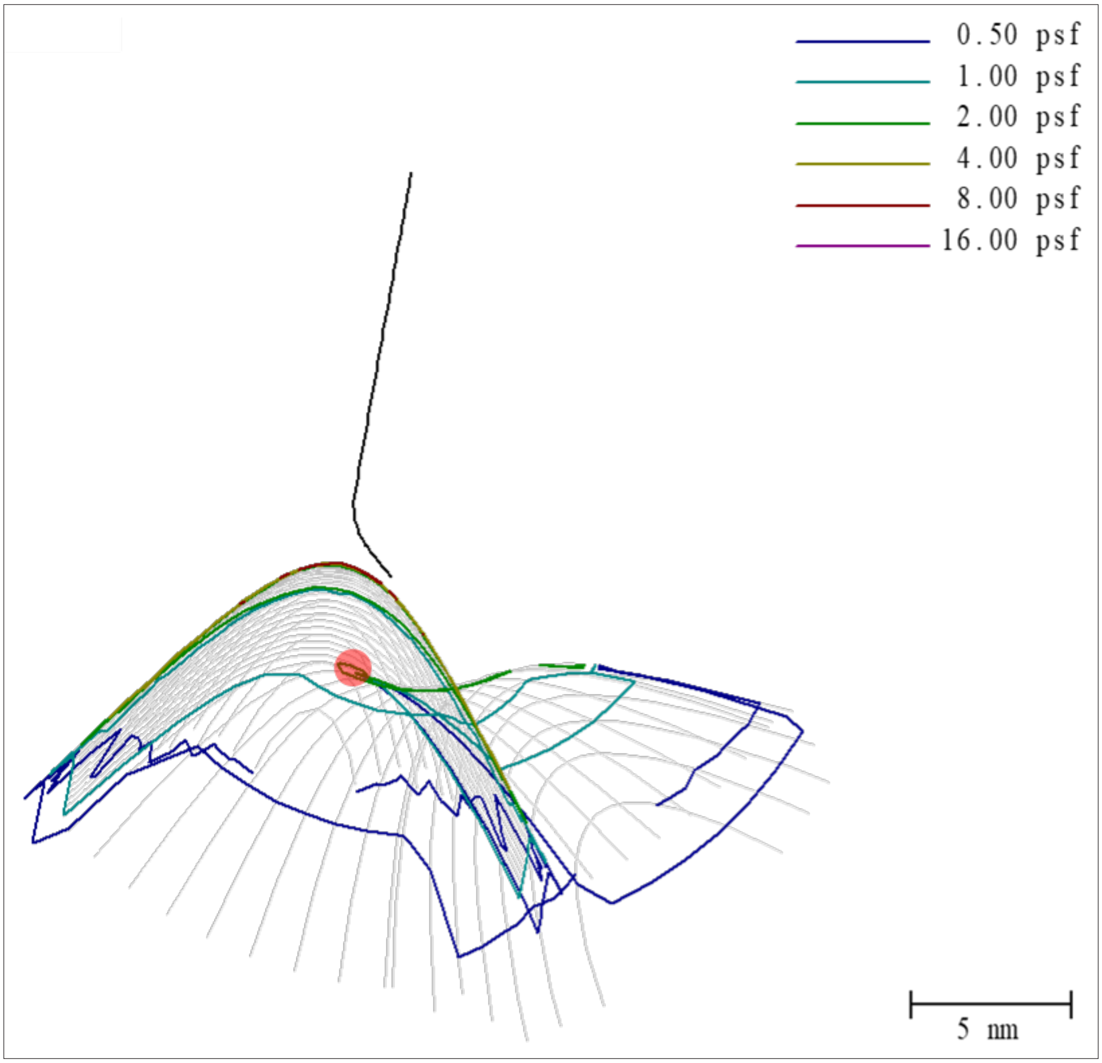
Figure 6 Illustration of a Sonic Boom Ground Intercept from a Level Acceleration to Supersonic Speeds



The U-waves result from the focusing of a very small portion of the sonic boom wave front. The region affected by such focused waves is small (*on the order of hundreds of square feet*). Adjacent regions are subjected to multiple N-waves or combinations of N-waves and post focus U-waves. Figure 6 illustrates the sonic boom ground intercept from a level acceleration from subsonic to supersonic speed. In this figure, the aircraft trajectory is upwards, and the small, focused boom region is at the start (*bottom*) of the sonic boom ground intercept (*Downing et al., 1998*).

A turning maneuver can generate another type of condition that produces a focus with enhanced overpressures called a "cusped focus." Figure 7 provides a representation of a sonic boom ground intercept for a supersonic turn maneuver. In the figure, the region of the "cusped focus" boom is highlighted in red. Overpressures within this cusped focus may be on the order of twice those produced by an ordinary focus, but the ground areas affected by cusped focuses are smaller compared to the regular focus region and significantly smaller compared to the overall footprint.

Figure 7 Sonic Boom Ground Intercept for a Supersonic Turn Maneuver

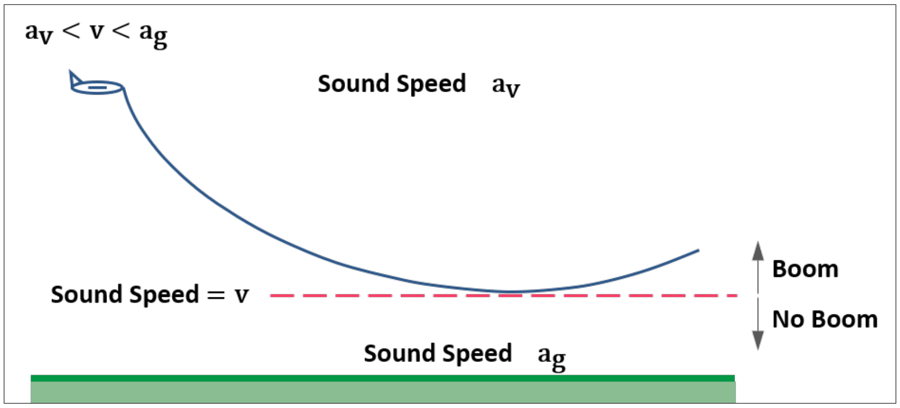


E. Sonic Boom and the Atmosphere

Depending on the aircraft's altitude, sonic booms reach the ground 2 to 60 seconds after flyover. However, not all booms reach the ground. The speed of sound at any altitude is a function of the air temperature. A decrease in temperature results in a corresponding decrease in sound speed. Under standard atmospheric conditions, air temperature decreases with increasing altitude. For example, when the sea-level temperature is 58 degrees Fahrenheit, the temperature at 30,000 feet drops to minus 49 degrees Fahrenheit. Thus, an aircraft at an altitude of 30,000 feet that is traveling at 680 miles per hour (*a supersonic speed at that air temperature*) would not be exceeding the speed of sound at ground level where the air temperature is higher (*see Figure 8*). As a result, the sonic boom generated at 30,000 feet would not reach the ground.

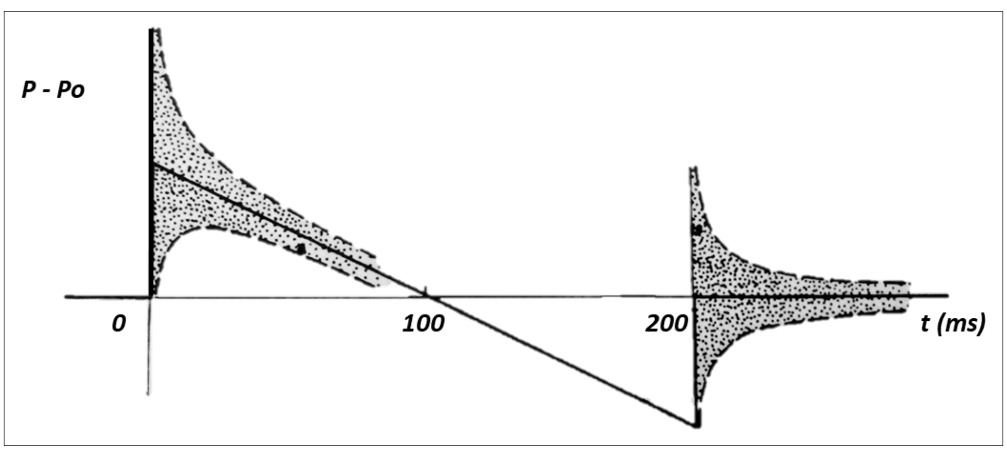
Said another way, for a sonic boom to be heard on the ground, the aircraft speed must exceed the speed of sound on the ground. The Mach number below which no sonic boom will reach the ground is referred to as the "sonic cutoff."

Figure 8 Flight at Sonic Cutoff Condition



Additionally, atmospheric turbulence modifies the shape of sonic boom waveforms. Studies have shown that the spiking and rounding of sonic boom signatures result from the effects of turbulence. From these earlier measurements of sonic booms, research developed a statistical envelope showing the effect of turbulence on sonic boom signatures, as shown in Figure 9 (*Crow, 1969*). This effect of atmospheric turbulence increases the uncertainty in the statistical modeling of sonic boom loading for actual sonic boom exposures. The general rule is that turbulence can result in a factor of two change in the peak overpressure of an N-wave. Turbulence can cause a 1 psf boom to vary from 0.5 (*rounded*) to 2 (*spiked*) psf. For focusing, the interaction is more complicated, but it does occur over a significantly smaller area.

Figure 9 Variance of a N-wave Sonic Boom Waveform because of Atmospheric Turbulence (Crow, 1969)



F. Computer Models for DOD Sonic Boom Analysis

1. PCBoom

PCBoom is used to calculate the location and magnitude of sonic-boom overpressures on the ground from individual supersonic flight of aircraft and space launch vehicles. PCBoom computes single-event sonic boom footprints and signatures from any supersonic vehicle executing any maneuver in a three-dimensional atmosphere, including winds and terrain effects (*Page et al, 2020*). This model has been verified with field measurements, and it accurately accounts for focusing of the sonic boom from aircraft maneuvers (*Downing et al, 1998*). The program has a menu interface that simplifies use and the presentation of results. The user specifies the aircraft, the maneuver, and atmospheric conditions. The primary outputs are the ground track of the trajectory and the sonic boom footprint in terms of psf contours of equal overpressure (*or other amplitude metrics*) on the ground, relative to the aircraft's position. PCBoom also generates sonic boom signatures, the pressure-time-histories, and spectra of booms at the ground. PCBoom is the DOD-approved model for single event sonic boom modeling (*DOD, 2020*).

A user has to supply PCBoom with a trajectory, atmospheric profile, wind profile (*if desired*), aircraft shape, function, and weight. A user has to develop a trajectory of the supersonic flight using their own tools. Unfortunately, no trajectory building tool is available for general use. Moreover, PCBoom does not check for physically accurate trajectory, so a user has to perform their quality checks on the input data.

The current version of PCBoom can be obtained from the National Aeronautics and Space Administration (NASA) Langley Research Center by sending a request via the following website: *https://software.nasa.gov/software/LAR-19926-1*.

2. BooMap

BooMap calculates the long-term sonic boom exposures from supersonic operations within authorized supersonic airspace. BooMap is used to calculate the cumulative sonic boom exposure from statistical representation of tactical military operations over a pre-defined geographic area, such as a military operations area. The model is based on a series of three monitoring efforts underneath three supersonic airspaces in the western United States (*Plotkin et al, 1989; Plotkin, 1990; Frampton, Lucas, and Cook, 1993*). These monitoring studies led to the determination that the noise exposure from sonic booms is governed by airspace boundaries, which can be generally described by elliptical contours. The metric calculated by BooMap is C-weighted Day-Night Average Sound Level (CDNL). A recent update to BooMap confirmed the elliptical contour shape (*Downing, Harker, and Lympany, 2021*). The updated model uses currently defined airspace boundaries or user-defined boundaries, user-supplied operational parameters, and monthly operational rates. The results are sensitive to the lower portions of the altitude distribution, so BooMap provides some reference altitude distributions, which are recommended to be used by most users. Single or multiple supersonic mission type can be modeled to best describe the supersonic operations within a given airspace. With the user supplies inputs, the model calculates the CDNL on a grid of points in the NMPlot Binary Grid Format, which is compatible with NMPlot. BooMap is the DOD-approved model for modeling cumulative noise exposure from supersonic operations (*DOD, 2020*).

3. Carlson's Simplified Sonic Boom Model

Carlson's Simplified Sonic Boom model is a simplified method for the calculation of sonic boom levels and durations (*Carlson, 1978*). It includes a wide range of supersonic vehicles including launch vehicles with operating altitudes up to 250,000 feet. The model predicts the sonic boom overpressures and duration as well as forward and lateral propagation distances for supersonic vehicles at a steady speed and in level, ascending, or descending flight paths. The ascending/descending angles are limited to moderate angles. This model provides quick estimates of sonic booms for comparisons between aircraft types and flight conditions. However, this model is not approved for use for sonic impact analyses since PCBoom is used for single event boom analyses.

PREVIOUS RESEARCH AND FINDINGS ON THE EFFECTS OF SONIC BOOMS

A. Human Response

Exposure to sonic booms at sufficiently high levels can annoy and startle people and may interfere with their sleep. At levels characteristic of residential exposure, sonic booms pose no realistic risk of hearing damage or any other impairment of health. These effects are described in greater detail in the next section, but first a brief discussion of the manner in which people perceive sonic booms is provided.

Sonic booms are short duration, rapid rise time noise events. If the N-wave pressure signature of a sonic boom has a short enough duration (*about a tenth of a second or less*), one hears it as a single “boom” sound. When the duration is greater than a tenth of a second, one hears each shock of an N-wave as separate impulses, which creates the distinctive “boom-boom” sound. This distinctive sound is not readily confused with more commonplace impulsive sounds such as fireworks, small arms fire, artillery, or backfiring of ground vehicles. Aircraft flying at close range generate sonic booms that are very loud with sharp cracks. Aircraft flying at great distances from observers generate sonic booms that are dull thuds or rumblings, which may be confused with distant thunder. Since much of the acoustic energy in sonic booms and other impulsive sounds is at very low frequencies, and since the A-weighting network is little affected by energy at such frequencies, it is possible for two sonic booms of the same A-level to differ greatly in magnitude. Therefore, sonic booms are characterized by their peak overpressure in psf and C-weighted Sound Exposure Level (SEL_C) since the C-weighting discriminates less against low frequency energy.

People do not directly hear but feel the bulk of the energy in sonic booms because human hearing is insensitive to sounds at the very low fundamental frequencies of sonic booms (*less than 10 Hz*). The only portion of a sonic boom that people directly hear is its higher harmonics, which contain far less energy than the fundamental frequency. However, structures respond to these low frequencies. The resonant frequencies of residential structures, for example, are commonly around 10 to 40 Hz. Thus, the energy in a sonic boom can cause shaking and rattling of loose-fitting doors, windows, wall hangings, cabinet contents, bric-a-brac on shelves, and other objects. This shaking can be visible, and the resulting secondary sound emissions may be audible. Thus, the effects of a sonic boom on household contents can potentially annoy residents even though they might not be able to hear the sonic boom that produced the rattling. A person may judge a sonic boom and the resulting rattling experienced indoors as more annoying than a boom of the same magnitude experienced outdoors (*Loubeau and Page, 2018; Page and Loubeau, 2019*).

In general, it is the shorter duration and higher overpressure sonic booms heard within the direct boom footprint that cause annoyance in communities, startle people, and give rise to complaints. Focus booms can be particularly startling because of their higher peak overpressures, but they cover a significantly smaller area within the direct footprint. Longer duration and lower-level booms can also give rise to community response because of their effect on structures. Sonic booms heard at points on the ground near the lateral cutoff of the direct boom footprint resemble low rumbles or distant, muffled thunder. High altitude supersonic flights can generate unique booms, called "over-the-top," which first propagate upwards and then back down to the ground. These over-the-top booms are inaudible because of their very low frequency content (*0.1 to 1.0 Hz*), but they can cause building vibrations that are readily observed. While this type of boom is rare for military flight, the retired Concorde aircraft did generate these booms, which placed further restriction on their supersonic flight because of very negative community response in New England.

1. Annoyance

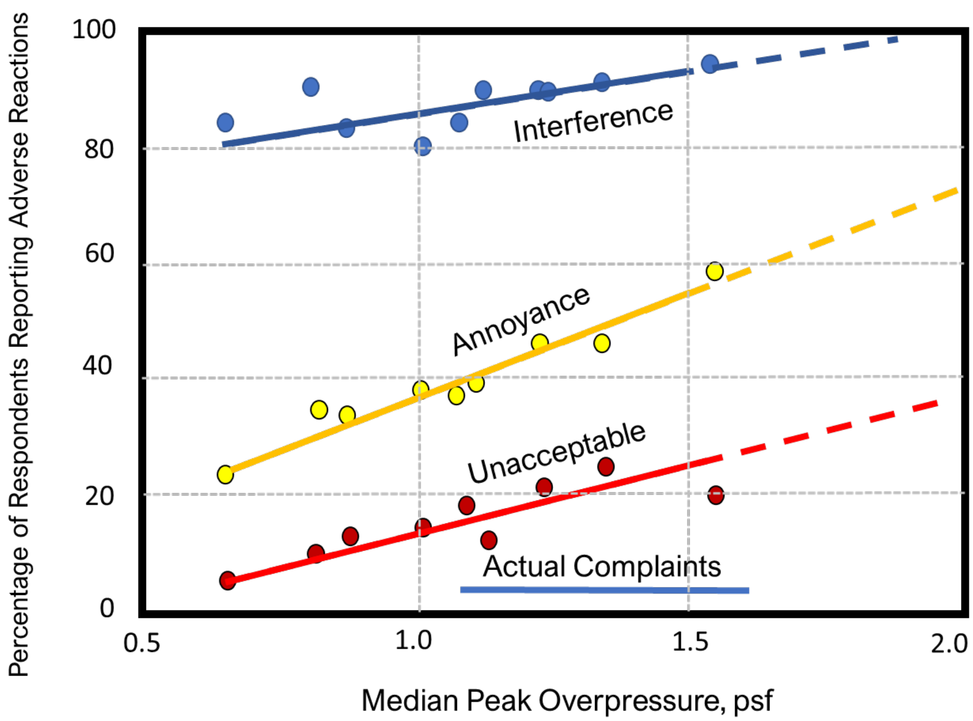
DOD and NASA sponsored several studies on the annoyance of sonic booms in the 1960s and 1970s. These studies supported the expected development of the SST aircraft, and they involved investigations both in the laboratory and in the field. Early tests in a small chamber by Pearsons and Kryter (*1965*) compared the annoyance of sonic booms with subsonic aircraft noise. The results of these empirical studies indicated that a 2.3 psf sonic boom heard outdoors was equivalent in annoyance to a subsonic flyover with a perceived noise level of 96 PNdB (*Amax = 83 dB*). A sonic boom of 2.3 psf (*measured outdoors*) heard indoors was judged equivalent in annoyance to a subsonic aircraft flyover with a perceived noise level of 113 PNdB (*Amax = 100 dB*).

These results agreed with those of an earlier study (*Broadbent and Robinson, 1964*), which found that test subjects listening indoors equated the annoyance of a 1.9 psf boom (*measured outdoors*) to that produced by a subsonic aircraft flyover at 95 PNdB (*Amax = 82 dB*). Shepherd and Sutherland (*1968*) studied the annoyance of simulated sonic booms as they would be heard outdoors. They reported that although the annoyance of a sonic boom was unaffected by a change in duration from 100 to 500 milliseconds, the annoyance did decrease as the rise time increased from 1 to 10 milliseconds.

In a field study with sonic booms created by a supersonic fighter aircraft, Rylander et al. (*1974*) conducted a social survey on residents exposed to low-level booms ranging from a fraction of a psf to 2 psf over a six-day period. Rylander and colleagues reported that people likened the booms of 0.4 psf and less to "distant thunder," and did not find them to be annoying. Sonic booms in the vicinity of 1 psf were likened to "moderate thunder," in relation to which fewer than 10% of the people interviewed in two exposed communities described themselves as "very annoyed."

To expand knowledge of long-term effects, a few projects exposed communities to multiple booms per day over extended time periods. These projects included social surveys to assess long-term community annoyance. As described in Section I.B, the most extensive of these was conducted over a six-month period in 1964 in Oklahoma City (*Hilton et al., 1964*). Residents of the city were exposed to a maximum of eight booms a day at overpressures of 1 to 2 psf. Von Gierke and Nixon (*1971*) provided a summary of the human response obtained during the study. Figure 10 captures the overall reporting of reactions to the long-term sonic boom exposures as a function of median peak overpressure along with linear curve fits. In this figure, task interference is the greatest percentage of respondents with over 80% reporting even for low sonic boom overpressures. Annoyance was the next highest response. The survey also included questions about the future of supersonic transport, so the survey included questions on acceptability of the boom exposure. For the lowest level of booms, the "unacceptable" response was less than 10%.

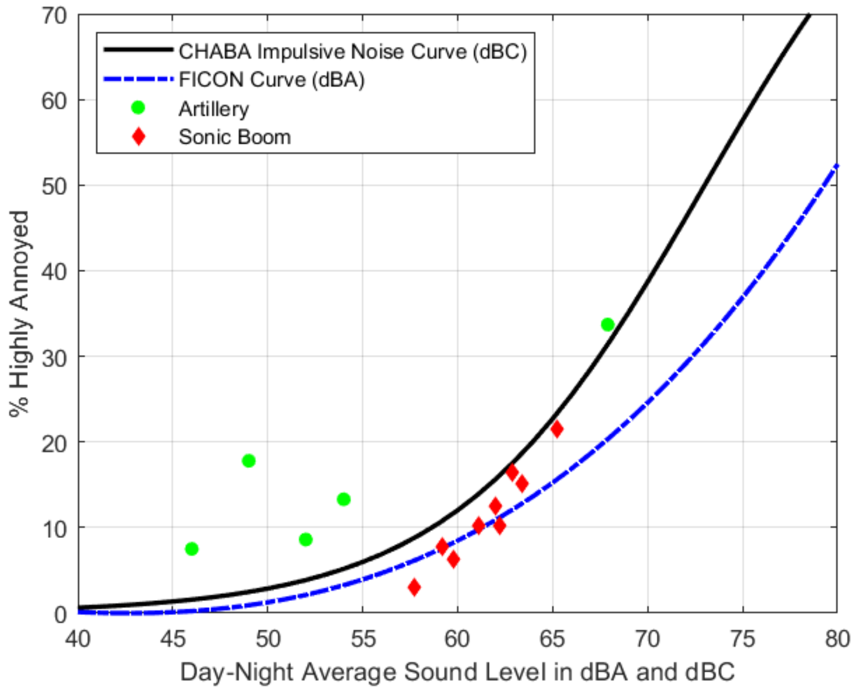
Figure 10 Response Data Summaries for the Oklahoma City Sonic Boom Project (von Geirke and Nixon, 1971)



The Committee on Hearing, Bioacoustics, and Biomechanics of the National Academy of Science's National Research Council Working Group 84 (CHABA) derived a doseresponse relationship between impulsive noise exposure and community annoyance. This relationship is based on a modest amount of social survey information about the annoyance of artillery fire, explosions, and sonic booms (*CHABA, 1981b*).

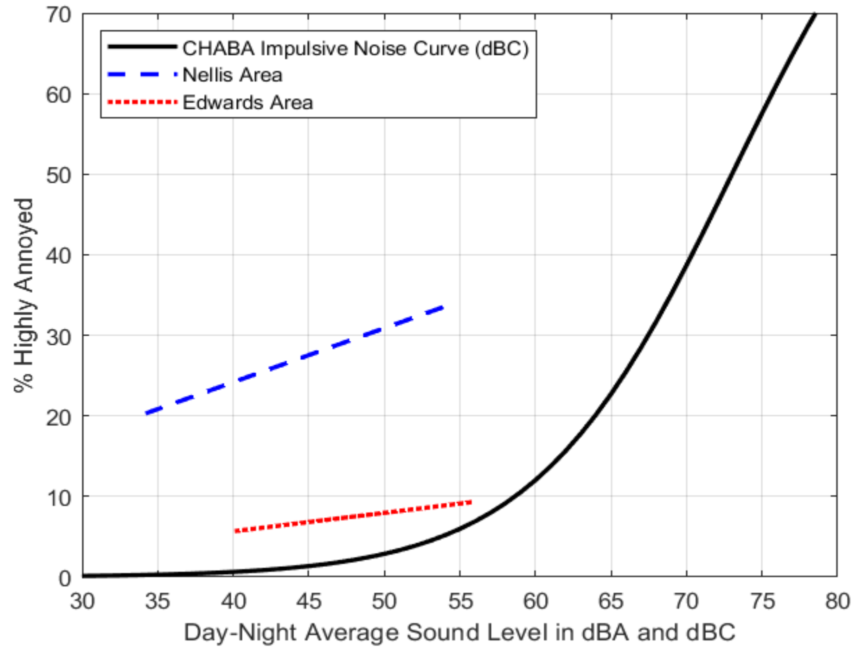
Figure 11 provides the graph of the recommended dose-response relationship for community response to high-energy impulsive noise along with the limited dataset. This figure also includes a comparison with the recommended Federal Interagency Committee on Noise (FICON) curve for transportation noise.

Figure 11 Recommended Relationships for Predicting Community Response to High-energy Impulsive Sounds and to Other Sounds (adapted from Galloway, 1981)



In the 1990s, the NASA High Speed Research Program sponsored two community studies in areas that have received sonic booms for many years (*Fields, 1997*). These areas included communities underneath or near supersonic airspace associated with Edwards AFB and the Nellis Test and Training Range. These areas have been regularly exposed to sonic booms from test and training operations for many years. These two studies included the measurement of sonic booms over a six-month period after which social surveys were completed. The cumulative sonic boom exposures as defined as Leq,24hr ranged from 34 to 56 dBC (*note that this metric was used since no acoustic nighttime booms were measured*). Figure 12 provides the results of the two surveys along with the CHABA curve. The results demonstrate a large variability in community responses to sonic booms. Part of this variation arises from the sporadic nature of boom exposures and other nonacoustical factors.

Figure 12 Comparison of Predicted Annoyance to Two Community Surveys (Field, 1997)



More recent studies from the 1990s to the present have concentrated on the influences of the sonic boom waveform shapes on annoyance (*e.g., Neidzwiecki and Ribner, 1978; Leatherwood, Shepherd, and Sullivan, 1991; Leatherwood and Sullivan, 1994; and Cliatt et al, 2014*). Many of these studies have concentrated on simulated sonic booms. Additionally, the motivation for these studies is the development of an acceptable supersonic transport aircraft for commercial air travel overland. Thus, the findings of these studies have limited application to military sonic boom noise.

Sonic booms are becoming a more important consideration as agencies explore new requests to permit overland supersonic travel by commercial carriers. NASA's "Quiet Supersonic Flights 2018 (QSF18) Test: Galveston, Texas Risk Reduction for Future Community Testing with a Low-Boom Flight Demonstration Vehicle" (*NASA, 2018*) evaluated public response to "low boom" exposure in a typical urban setting. The overpressure of a controlled dive produced a sound (*called a "sonic thump"*), and the test laid the research foundation for an understanding of dose response and the FAA's regulatory work on certification of overland supersonic travel. The follow-on is NASA's Quiet SuperSonic Technology (Quesst) Mission (*https://www.nasa.gov/X59*), which will design and build a low boom demonstrator aircraft (*X-59*) and perform community tests to gather human response data.

Another important aspect of the previous human and community response studies is their focus on people in a residential setting. However, sonic booms may annoy people in occupational and recreational as well as residential settings. For example, sonic booms may annoy outdoor recreationists, particularly those seeking solitude or other wilderness experiences. The U.S. Department of Agriculture Forest Service and

NASA have made preliminary but inconclusive efforts to measure sonic boom effects in an officially designated wilderness (*Sneddon, Silvati, Pearsons, and Fidell, 1991*). The degree of individual annoyance caused by sonic booms among visitors to remote park and wilderness areas is not known with useful precision. Sonic booms may also annoy people in outdoor occupational settings, such as ranchers and others who earn their living outdoors.

2. Startle

Sonic booms, like other sudden, unexpected high-level sounds, can startle people. The startle response (*i.e., involuntary gross motor movement, eye blink, orientation toward the apparent source*) is a generic one with no long-term physiological significance.

The results of Rylander and colleagues' (*1974*) study of startle produced by sonic booms are typical. Volunteers were exposed to 5 to 12 booms with overpressures ranging from 1.2 to 12.8 psf. Startle effects were gauged by a hand-steadiness test, measurement of heart rate, and a tracking test. Boom-induced startles produced the expected momentary gross muscular movements and a slight increase in heart rate. The average increase in heart rate was about 2 beats per minute. Habituation occurred after about 10 sonic boom exposures.

Startle produced by noise exposure varies greatly with individuals and the nature of the sound source. Impact noises with peak overpressures comparable to those of sonic booms (*2 to 3 pounds psf*) include pile-drivers, metal-beating and drop-forging, firecrackers, fireworks, and handgun firing. Habituation to expected exposure of this sort is commonplace and rapid (*EPA, 1973*).

3. Sleep Interference

It is a matter of common experience that noises can disturb sleep. Since supersonic flight during nighttime hours is rare, awakenings due to sonic booms are uncommon. Nonetheless, a non-negligible fraction of the population habitually sleeps during daylight hours, including night shift workers, very young and very old people, people who are sick, etc.

Direct empirical evidence of the ability of sonic booms to disturb sleep is very scarce. During the SST Program, only four studies were conducted on sleep awakenings from both simulated and actual sonic booms (*Collins and Lampietro, 1973; Ludlow and Morgan, 1972; Lukas, Dobbs, and Kryter, 1971; and Lukas and Dobbs, 1972*). A review of these studies combined their results to develop a relationship between sonic boom levels and awakenings (*Pearsons, Barber, and Tabachnick, 1989*). A preliminary dose-response relationship for awakenings due to impulsive noise exposure is as follows:

Eq. 1 % Awakened or Aroused = 2.32(CSEL) - 184.9

4. Task and Communication Interference

Anecdotal evidence and common experience suggest that startle due to unexpected sonic booms could adversely affect performance of tasks requiring intense concentration (*e.g., surgery*). On the other hand, many tasks are almost certainly unaffected by momentary disruption. In general, the effects of impulsive noise exposure on task performance are influenced as much by nonacoustical factors (*e.g., nature of the task, skill level, habituation*) as by noise levels.

Sonic booms do not interfere meaningfully with speech intelligibility. The acoustic masking effect of a boom is negligible because its duration is only a fraction of a second and the bulk of its energy is in frequency regions that convey no speech information. However, the attention given to a sonic boom immediately after its occurrence, conversation and comments about it, and the resulting disruption of group activity can all produce extended interruptions.

5. Hearing Damage Risk

Based on the application of findings reported in CHABA's (1992) review document, impulsive noise exposure produced by occasional overflights of supersonic aircraft poses no meaningful risk of hearing damage for several reasons. The two most notable are 1) occasional sonic booms produced on the ground by aircraft overflights at typical operating altitudes are far too low in sound pressure level and too infrequent in occurrence to cause either temporary or permanent threshold shifts, and 2) the rise time of a typical sonic boom is much too long (*or equivalently, the high frequency content is much too low*) to harm hearing mechanisms.

Evidence that the high-frequency spectral content of sonic booms is inadequate to damage hearing is available from studies conducted in 1968 at Tonopah, Nevada. Sonic booms with overpressures ranging from 50 to 144 psf caused no direct injury to exposed test subjects. Tests on subjects exposed to simulated air-bag noises at peak levels as high as 80 psf showed that small, temporary threshold shifts in hearing were mainly caused by high-frequency noise, rather than the low-frequency energy typical of sonic booms (*Sommer and Nixon, 1973*).

6. Non-Auditory Health Effects

The U.S. Air Force (USAF) sponsored a study in the 1980s to compare long-term sonic boom exposures to human health data in Nevada (*Kamerman et al, 1986; Anton-Guirgis et al, 1986*). Nevada was selected since military supersonic operations have been conducted within its boundaries longer than any other location in the United States. The first part of the study developed estimates of the sonic boom exposures from 1969 to 1983 to align with the health data. The second part involved an epidemiological study using state-wide mortality and hospital morbidity data from the same time period. The study found no evidence linking adverse health effects with longterm sonic boom exposures.

The USAF also sponsored a comprehensive review of the effects of aircraft noise and sonic booms on non-auditory health (*Thompson, Fidell, and Tabachnick, 1989*). Thompson et al. reviewed a very large prior literature survey on effects of noise on the cardiovascular system (*Thompson, 1981*); analyzed methodological problems inherent in attributing non-auditory health effects to aircraft noise exposure and sonic booms; generated a general process model of noise impacts on health; evaluated alternative means for performing research on noise effects on health; and developed criteria and a design for a credible longitudinal study of aircraft noise on cardiovascular health.

Thompson et al. (*1989*) concluded that no epidemiologic evidence exists of any nonauditory health effects of either episodic or chronic sonic boom exposure. They further noted that existing evidence is composed largely of studies reporting geographic associations, the weakest form of epidemiological evidence. Thompson et al. noted additional complicating factors that prevent the determination of causality to any association between aircraft noise and adverse health consequences. These complicating factors include the lack of specific biological markers for noise-induced non-auditory effects, poor general understanding of stress-induced disease processes in the cardiovascular system, the long development of cardiovascular disease, an inability to distinguish noise-induced risks from other health risks, the difficulty of measuring personal aircraft noise exposure, and the impossibility of experimentally controlling aircraft noise exposure.

The findings of Thompson et al. (*1989*) update those of a previous review undertaken by CHABA (*CHABA, 1981*) of non-auditory health effects of impulsive noise exposure. CHABA investigated whether noise standards established to safeguard hearing are sufficient to protect against health disorders other than hearing damage. CHABA noted that published information:

> *"…does not provide definitive answers to the question of health effects, other than to the auditory system, of long-term exposure to noise. It seems prudent, therefore, in the absence of adequate knowledge as to whether or not noise can produce effects upon health other than damage to the auditory system, either directly or mediated through stress, that insofar as feasible, an attempt should be made to obtain more critical evidence." (*CHABA, 1981*)*

CHABA's report notes that many published studies exhibited major methodological flaws, such as inadequate control for known risk factors other than noise.

Considering the relatively small number of sonic booms and the low levels of exposure to which most residential populations are exposed, it is highly unlikely that sonic boom exposure produced by DOD operations may adversely affect the health of the exposed population.

B. Potential for Structure Damage

Beginning with the earliest supersonic overflights in the 1950s, some supersonic flights have generated unexpected property damage to structures. Ongoing targets of research have been to identify candidate mechanisms that may have resulted in this damage, to understand the operation of these mechanisms, and to evaluate their credibility. Hypotheses to explain unexpected damage have fallen into the following categories: 1) mechanisms that produce higher than anticipated loads, 2) mechanisms that produce above average response from a given load, and 3) factors that result in diminished structural capacity (*Haber et al., 1989*).

Major sonic boom damage incidents have occurred from supersonic flights over built-up areas. An example is an incident at the U.S. Air Force Academy on 31 May 1968 (*Associated Press, 1968*). This incident resulted when an F-105 went supersonic during a low-level, high-speed demonstration pass. The pass caused extensive window breakage, plaster failures, and some injuries from flying glass. The estimated level of the sonic boom hitting the buildings was well above 100 psf.

The strongest sonic boom ever recorded was 144 psf, and it did not cause any injury to the exposed researchers. This boom was produced by an F-4 flying at an altitude of 100 feet at a speed just above the speed of sound. In another sonic boom test, the maximum focused boom (*Uwave*) measured during more realistic flight conditions was 21 psf. These intense sonic booms have a probability to generate some structural damage, such as broken glass. This potential for damage is a primary reason why supersonic airspace is only over bodies of water or very sparsely populated land areas.

Table 1 provides a summary of potential damage to conventional structures. The rate of damage is highly variable because of the multiple factors involved with sonic boom interaction with a given structure. Generally, buildings in good structural condition should have a low rate of potential damage by overpressures of less than 10 psf. Minor damage, such as window failures (*cracks*), may occur between 2 and 4 psf. However, this occurrence is rare. Typically, community exposure to sonic booms is below 2 psf. Ground motion resulting from sonic boom is rare and is considerably below structural damage thresholds accepted by the U.S. Bureau of Mines and other agencies.

Table 1 Possible Damage to Structures from Sonic Booms (Haber and Nakaki, 1989)

Nominal Level	Structural Element	Damage Type
0.5–2 psf	**Glass**	Extension of existing cracks; potential for failure for glass panes in bad repair; failure potential for existing good glass panes is less than one out of 10,000 at 2 psf.
	Ceiling Plaster	Fine cracks; extension of existing cracks; mostly from fragile areas.
	Wall Plaster	Fine cracks; extension of existing cracks (*less than in ceilings*); over doorframes; between some plasterboards; mostly fragile areas.
	Roof	Older roofs may have slippage of existing loose tiles/slates; sometimes new cracking of old slates at nail hole; new and modern roofs are rarely affected.
	Bric-a-brac	Those carefully balanced or on edges can fall; fine glass, such as large goblets, can fall and break.
2–4 psf	**Glass**	Failures show that would have been difficult to forecast in terms of their existing localized condition. Nominally in good condition.
	Ceiling Plaster	Estimated rate of cracking ranges from less than one out of 5,000 (*2 psf*) to one out of 625 (*4 psf*).
	Wall Plaster	Estimated rate of cracking ranges from less than one out of 10,000 (*2 psf*) to one out of 1,000 (*4 psf*).
	Roof	Potential for nail failure if eroded.
	Bric-a-brac	Increased risk of tipping or falling objects.
4–10 psf	**Glass**	Regular failures within a large population of well-installed glass (*one out 50 [*10 psf*] to 500 [*4 psf*]*); Failure potential in industrial and greenhouses glass panes.
	Ceiling Plaster	Estimated rate of cracking ranges from one out of 625 (*4 psf*) to one out of 10 (*10 psf*). Potential for partial ceiling collapse of good plaster; complete collapse of very new, incompletely cured, or very old plaster.
	Wall Plaster	Estimated rate of cracking ranges from less than 1 out of 1,000 (*4 psf*) to one out of 50 (*10 psf*). Measurable movement of inside (*"party"*) walls at 10 psf.
	Roof	Regular failures within a large population of nominally good slate, slurry-wash; some chance of failures in tiles on modern roofs; light roofs (*bungalow*) or large area can move bodily.
	Bric-a-brac	Increased risk of tipping of falling objects.
>10 psf	**Glass**	Some good glass will fail regularly (*greater than one out of 10*) due to sonic booms and at an increased rate when the wavefront is normal to the glass pane. Glass with existing faults could shatter and fly. Large window frames move.
	Ceiling Plaster	Plasterboards displaced by nail popping.
	Wall Plaster	Most plaster affected. Internal party walls can move even if carrying fittings such as hand basins or taps; secondary damage due to water leakage.
	Roofs	Most slate/slurry roofs affected, some badly; large roofs having good tile can be affected; some roofs bodily displaced causing gale-end and will-plate cracks; rarely domestic chimneys dislodged if not in good condition.
	Bric-a-brac	Some nominally secure items can fall (*e.g., large pictures, especially if fixed to party walls*).

C. Land Use Planning

DOD has not adopted formal guidelines for land use compatibility with high-energy impulsive noise exposure. One approach to determine impulsive noise levels for land-use planning is to infer via the equivalent percentage highly annoyed between the CHABA impulsive and general transportation noise curves. This approach assumes an equivalence of exposure of C-weighted to A-weighted cumulative exposure units that are estimated to produce the same level of community annoyance.

For example, the U.S. Army uses this approached in Chapter 14 of U.S. Army Regulation 200-1, "Operational Noise" (*13 December 2007*), with respect to impulsive noise exposure. This regulation uses the original Schultz curve (*1978*) to estimate the equivalent levels for impulsive noise. FICON recommended an updated community annoyance curve for general transportation in 1992 that results in different equivalent levels for impulsive noise compared to the original Schultz curve. Table 2 provides comparison of the equivalent levels using the two dose-response curves. In the range of interest, differences in the slopes of the latter two logistic fitting functions (*FICON and CHABA*) give rise to an approximate 5 dB difference in the criterion levels as expressed in A- and C-weighted cumulative exposure units.

Table 2 Land Use Compatibility Guidance Inferred from Equivalent Prevalence of Annoyance Associated with A-weighted and C-weighted Day-Night Sound Levels

Compatibility with Single and Multiple Family Residential Land Uses (*per ANSI S12.9-2007 Part 5*)	DNL, dBA	Equivalent Level, CDNL (dBC)	
		Schultz Curve	FICON 1992 Curve
Normally compatible	50	44.6	46.0
Marginally compatible with single family, extensive outdoor use	55	52.1	50.6
Marginally compatible with multiple family, moderate outdoor use and with multi-story, limited outdoor use	60	57.5	55.2
Compatible with insulated multistory use; incompatible with single and multiple family use	65	61.8	59.7
Incompatible with any residential land use	75	69.5	68.9

Although such equivalences can serve on an interim basis until a larger body of direct evidence about the annoyance of sonic boom exposure is available, they should not be treated as definitive guidance on land use compatibility.

DISCUSSION

A. Why Do Sonic Booms Matter?

The technology of supersonic flight and low-boom has advanced to the point that overland commercial travel is viable. The FAA is developing regulations for overland supersonic flight, and NASA is defining a dose/response relationship for low-boom exposure. As a result, in the foreseeable future, the general public will be reaping the benefits of faster travel while being exposed to mild sonic booms on a regular basis. However, the nature and exposures of sonic booms from commercial air travel will be much different compared to sonic boom exposures from DOD supersonic operations. Commercial supersonic operations will span the entire nation on a network of flight routes and occur many times a day. On the other hand, military supersonic operations occur in restricted airspaces and on a more sporadic schedule over low-population areas. Therefore, commercial supersonic operations must generate low-boom waveforms for acceptance by the public. Military supersonic operations will continue to generate N-wave and focused booms within confined areas.

At the other end of the spectrum, increased access to earth orbit and space by launch vehicles will generate traditional sonic booms. Touchdowns on land by reusable rocket stages, passenger flights, orbiting crew returns, and cargo shipments are all new sources of sonic booms. An understanding of the impacts and possible mitigation techniques of supersonic flight will improve decision making and mission success. The science behind sonic booms will inform landing site selection, flight trajectory, ground support procedures, and public preparedness. It will also facilitate deeper, more nuanced questions that will hone realistic expectations.

B. Implications for Airspace and Ranges

The tactical pilot training requirements will not change dramatically in the foreseeable future, but they are continuing a transition to lower and faster flights in response to near-peer adversary capabilities. Consequently, sonic boom events from training have increased in airspace, ranges, and military operating areas.

The airspace in which space launches are conducted is generally over water, so the sonic booms do not affect residents. But the return landings of space vehicles and components on land after their mission will be accompanied by sonic booms that will be experienced in the vicinity.

FINDINGS/CONCLUSIONS

DOD requires the use of PCBoom and BooMap for sonic boom exposure modeling (*DOD, 2020*). PCBoom is used to model the sonic boom footprint for a single supersonic trajectory, and the general output is contours of equal psf related to the peak overpressure of the sonic boom. The levels of psf used for analysis depend on the various effects being analyzed. BooMap models the cumulative noise exposure from supersonic operations within a supersonic airspace. The output is elliptical contours of equal CDNL values. The levels used to assess impacts are listed in Table 2.

The primary effect of sonic booms on residential populations is annoyance. The community annoyance due to sonic boom exposure is best predicted on the basis of the dose-response relationship developed by CHABA (*Galloway, 1981*). This relationship includes any annoyance associated with startle and speech interference. NASA's recent research and development of low boom designs demonstrates that sonic booms need to be low-level for general public acceptance with the forecasted multiple daily supersonic flights across the nation. Since military sonic booms are sporadic and confined to selected training areas, NASA's acceptance criterion does not apply to military supersonic operations.

Residential exposure to sonic booms poses no meaningful risk of hearing damage. Nor has any study shown evidence that residential exposure to sonic booms poses a plausible risk of harm to non-auditory health.

Generally, buildings in good condition have minimal damage by overpressures of less than 10 psf. Older and poorly-maintained structures can suffer from the vibration caused by low-frequency sound. The most serious property damage from sonic booms to structures has resulted from low altitude (*>10,000 ft MSL*) supersonic flight near structures, either as a part of field tests of the effects of sonic booms on structures or because of a pilot inadvertently flying supersonically during a low-level pass. Extremely high overpressure incidents of this type are rare enough so that, when they do occur, they can cause significant damage and attract media attention. Lesser accidents are more common although still infrequent. These may break large numbers of windows, dislodge loose paint or plaster, and topple bric-a-brac.

In the absence of human errors, sonic boom damage is rare. Sonic boom damage is most likely to occur when windows are pre-stressed, when poor workmanship practices are applied to installing plaster ceilings or walls, when structures are poorly maintained, and when a building configuration is susceptible to enhanced sonic boom loads.[2] These damage levels are commonly much smaller than those resulting from accidents.

The assertion of cumulative damage from sonic booms is not a factor for structural elements in good repair. For elements with pre-existing damage, repeated sonic booms may contribute to further damage. The contribution of sonic booms to the increased damage may be minor compared to other human-made and environmental loads that are of comparable or greater magnitude. Damage to structural elements such as foundations, rafters, and beams is highly unlikely.

2 *Examples of buildings with the potential for enhanced loads are buildings with large windows facing the inbound sonic boom and buildings with resonant frequencies overlapping a sonic boom spectrum.*

SUGGESTED READING LIST

Concorde: The Rise and Fall of the Supersonic Airliner, Jonathan Glancey, 2015

Quieting the Boom: The Shaped Sonic Boom Demonstrator and the Quest for Quiet Supersonic Flight, Lawrence Benson, 2013

Faster Than Sound: The Story of Supersonic Flight, Bill Gunston, 1992

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As members of the community, the Military Services (*i.e., Army, Navy, Marine Corps, Space Force, Air Force*) want to be good neighbors. The Military Services continue to work with civilian partners and listen to residents' concerns regarding the sounds associated with military training that may be disruptive to our community. Military Service staff are available to meet and discuss noise associated with military training. Contact the local Public Affairs Office or the Community Plans and Liaison Officer with any questions or concerns.

For more information or questions about the DOD Noise Program, please contact us at: *osd.noiseprogram@mail.mil*.

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