Human Perception of Sonic Booms from Supersonic Aircraft

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Advances in human response research will help pave the way for a new era of commercial supersonic flight.

Introduction

The lure of faster speeds and reduced travel time for commercial flights may come to fruition soon with advances in low-boom technology. The Concorde "was a technological marvel that astounded the world with its beauty of design and speed, halving passenger flight times to distant destinations" (Rogers and Maglieri, 2015). Its last flight on October 24, 2003, ended the first era in supersonic commercial travel. Although supersonic flight of the Concorde resulted in loud sonic booms, decades of low-boom research have demonstrated the feasibility of adapting the aerodynamic shape and tailoring the off-body pressure distribution from a supersonic vehicle to decrease or control the sonic boom, a technique known as sonic boom shaping. Sparrow (2006) provides a snapshot of the history of sonic boom minimization. With this new technology, research of the human response to sonic boom noise is being conducted to better understand the factors that contribute to annoyance from sonic boom sounds so that they can be "shaped" for minimal disturbance, thereby potentially resulting in a new era in supersonic commercial travel. Indeed, recent advances in understanding and predicting human perception of sonic booms have coincided with renewed interest from industry in pursuing development of a new generation of quiet commercial supersonic aircraft and have also led to the new lexicon "sonic thump" that reflects their quieter sounds (explained in **Unique Qualities of Sonic Booms**).

Low-frequency energy, the transient nature of the sound, and high-frequency energy at shocks are qualities of sonic booms that differ from conventional subsonic aircraft noise. Thus the noise metrics that are currently used for airport noise cannot be used for evaluation of community annoyance and acceptance for sonic booms. Although perceived level (PL; Stevens, 1972) has been identified as a preferred metric (Leatherwood et al., 2002) for describing sonic boom annoyance in outdoor environments, there is no internationally agreed on standard noise metric that can be used to quantify the sonic boom level.

Data gathered from planned future community tests with a supersonic demonstrator aircraft will be provided to regulatory organizations such as the International Civil Aviation Organization (ICAO) to provide the scientific basis for development of new noise certification standards for supersonic aircraft. Today's research will help prepare for this future community testing to ensure gathering of accurate data in an efficient manner.

Unique Qualities of Sonic Booms

The transient nature of the sonic boom and large amount of low-frequency energy in the signal result in a sound character that is perceived much differently

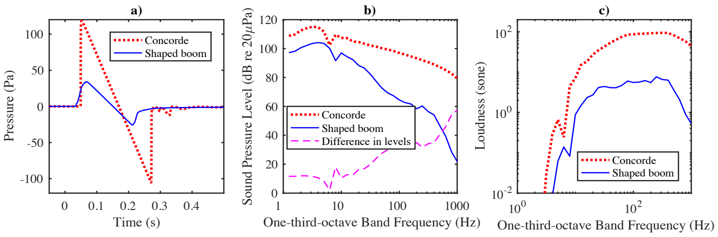

Figure 1. *Comparison of sonic boom waveforms and spectra for the Concorde and an airliner concept designed for low-amplitude shaped booms (J. Klos, personal communication).* ***a****: Examples of boom shapes.* ***b****: Variation in frequency spectra.* ***c****: Variation in loudness spectra.*

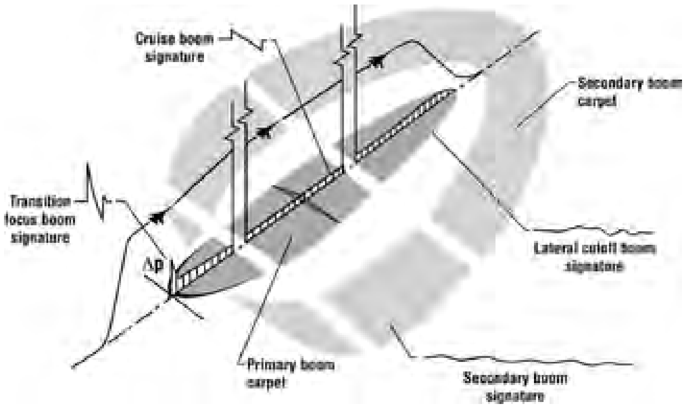

Figure 2. *Schematic of sonic boom ground exposure (Maglieri et al., 2014).* ***Dark gray****, primary boom carpet with an N-wave conventional sonic boom. At the edge of the primary carpet is the lateral cutoff edge with a unique signature that generally does not contain large shocks.* ***Light gray****, secondary boom carpet containing waveforms with indistinct characteristics that sound like rumbles or distant thunder. The transition from subsonic to supersonic flight creates a focused sonic boom signature with an accentuated high-amplitude initial shock. The black and white under the centerline of the flight track and across the carpet indicate the relative overpressure levels (Δp) for the different segments of flight.*

than the sounds from conventional aircraft. Although subsonic aircraft noise is a concern near airports, the sonic booms from supersonic aircraft are created along the entire supersonic route and could potentially affect large segments of the population.

With advances in aircraft-shaping techniques, modern supersonic aircraft designs are predicted to create shaped low-amplitude sonic booms heard on the ground that are much quieter than conventional N-wave sonic booms from the Concorde (see **Figure 1**). The significant reduction in waveform amplitude and increase in shock rise time lead to a reduction in sound pressure level spectra, particularly at higher frequencies where the reduction can reach 60 dB. Accordingly, the loudness spectra are also reduced by over a factor of 10 in sones over most of the frequency range critical to human hearing. This reduction in the high-frequency content results in a sound like a "thump" rather than a sharp crack or boom.

Historically, the maximum overpressure was used to describe the level of sonic booms. Years of research using outdoor sonic boom simulators, however, resulted in identification of PL (Stevens, 1972; Shepherd and Sullivan, 1991) as a noise metric that works best for a variety of signature shapes (Leatherwood et al., 2002). Annoyance to sonic booms experienced indoors presents additional factors related to the building itself.

The Sonic Boom Carpet

Sonic booms are pressure disturbances caused by supersonic flight that reach the ground. **Figure 2** shows the different regions of sonic booms including the primary boom carpet, the transition focus, and the secondary boom carpet.

Sonic Boom Noise Generation for Subjective Studies

Laboratory simulators have been used effectively to study human annoyance to a broad range of sonic boom signals under controlled conditions (Maglieri et al., 2014). Simulators can reproduce measured booms as well as booms predicted for aircraft designs. They can also be used to investigate the human response to different waveform parameters and interactions. The majority of simulators reproduce sonic booms as they would be experienced outdoors, although filtered outdoor waveforms or recordings of indoor waveforms have also been presented to estimate the indoor environment. Most simulators, however, lack indoor realism because there is an absence of space and reverberation as well as of structural vibrations and rattle. These structural vibrations that occur in a building when impacted by a sonic boom result in contact-induced rattle noise from elements such as windows, doors, and objects inside rooms.

Most outdoor sonic boom simulators consist of an airtight, small rigid-walled booth. The cavity is driven with subwoofer loudspeakers to reproduce the low frequencies characteristic of sonic booms, whereas midrange loudspeakers fill in the rest of the pertinent spectrum. Another simulator design consists of a mobile trailer that creates a traveling wave using an array of loudspeakers, a folded horn, and an anechoic termination (Salamone, 2005).

High-quality headphones or earphones are also used to reproduce the audible content of sonic booms and secondary rattle noises typically encountered in indoor environments.

Binaural signals have been used to approximate the auditory experience of sonic boom and rattle exposure in different-sized rooms through the use of models and filtering (Giacomoni and Davies, 2013; Loubeau et al., 2013c). Some limitations of this playback equipment are the absence of experiencing the sounds in a real space with natural reverberation, the absence of tactile vibration, and decreased realism due to limited low-frequency reproduction. High-quality systems of amplifiers and headphones have mitigated this last point somewhat, but the systems are still more restricted than subwoofer systems for reproducing the full frequency content of the sonic booms.

Finally, newer simulators allow for more realistic indoor soundscapes for investigating causes of elevated annoyance to sonic booms experienced indoors. One configuration (Naka, 2013) consists of a small booth that can be configured for indoor listening using a partition with a window. Another installation called the Interior Effects Room (IER; Klos et al., 2008) at the NASA Langley Research Center consists of a small room configured as a living room with loudspeaker playback over arrays adjacent to two exterior walls of the simulator. The realistic indoor soundscape and environment, augmented with the ability to control secondary rattle noises and vibration, have enabled systematic studies of the factors contributing to human annoyance to sonic booms.

Sonic boom subjective studies have also been conducted with real supersonic overflights of aircraft. In the past, these studies were limited to assessing the response to very loud booms, usually produced with military aircraft. However, a special flight maneuver called a low-boom dive has been developed (Haering et al., 2006) to mimic the lower amplitudes at the ground that would be expected from supersonic overflight of future aircraft. By adjusting the location of the dive, and hence the propagation distance, the ground sonic boom can be varied in level over a geographic area.

This maneuver has been used successfully in several field studies to create a variety of boom loudness levels that would otherwise not be possible with today's aircraft in steady, level flight. This dive maneuver is not without limitations for dose-response testing though because it creates a double boom of low-amplitude N-waves. In this maneuver, the aircraft executes an inverted dive from 50,000 feet and transitions to level flight above 30,000 feet (see Sparrow, 2006 for a diagram of the maneuver). The aircraft creates shock waves continuously while it is moving faster than Mach 1. The first boom to arrive at the area of interest is from the latter part of the dive, whereas the second boom is from the earlier part of the dive because the supersonic speed of the aircraft has allowed it to outrun the propagating waves!

Human Response Studies

Human Response to Outdoor Booms

Many human response tests were performed in NASA's outdoor sonic boom simulator in the 1990s (Leatherwood et al., 2002). These laboratory studies were designed to investigate a wide range of shaped sonic boom signatures and to gather human perception of loudness and annoyance. Shaped booms were rated less loud than symmetric N-waves, and several noise metrics were evaluated for their ability to predict the subjective response. As a result of PL being chosen as the best noise metric, it has since been used widely to design and assess characteristics of supersonic aircraft.

Evaluation of the realism of outdoor boom simulation was conducted with simulators and real booms from overflights of a supersonic aircraft (Sullivan et al., 2008). PL values were found to be highly correlated between field recordings and simulator reproduction, and the results increased confidence in the use of simulators for human response testing. It was noted that very low frequency energy (less than 7 Hz) was not significant for assessing realism to booms experienced in an outdoor environment.

Outdoor Versus Indoor Response

A field study conducted by NASA compared perception ratings from test subjects seated inside and outside a house overflown by a supersonic airplane using the low-boom dive maneuver (Sullivan et al., 2010). Although the annoyance ratings showed that indoor and outdoor annoyance were the same for the same noise exposure, a posttest questionnaire highlighted an increase in annoyance indoors. This inconsistency could possibly be attributed to the methodology chosen or to the presence of a rattle indoors.

A series of subjective tests with playback of measured low-amplitude sonic booms was conducted (Miller, 2011) to further explore the inconsistency discovered by Sullivan et al. (2010). Three different listening environments were explored, including headphones indoors, headphones outdoors, and an outdoor simulator (Salamone, 2005), and the same set of signatures was used in each case. Active listeners found indoor signatures more annoying than outdoor signatures regardless of listening environment, and signatures experienced indoors were considered more annoying.

A series of simulator tests was also conducted by the Japan Aerospace Exploration Agency (JAXA; Naka, 2013) to evaluate loudness and annoyance ratings of N-waves with different amplitudes and rise times, using both indoor and outdoor configurations. The JAXA tests evaluated loudness and annoyance and found that indoor ratings were higher than outdoor ratings for a given loudness level.

Human Response to Indoor Booms

In recent years, sonic boom subjective research has shifted to exploring perception of booms experienced indoors. Initial studies in NASA's IER simulator found that boom amplitude and rise time persist as important factors for an indoor response (Rathsam et al., 2012; Loubeau et al., 2013a). Overall, the longer rise times of low booms result in decreased annoyance.

To assess the feasibility of utilizing a subscale flight demonstrator, a comparison of indoor annoyance to sonic booms predicted for subscale and full-scale supersonic aircraft (which have different low-frequency energy, even for the same overall loudness value) was conducted (Loubeau, et al., 2013b; Loubeau, 2014). The test used shaped, low-amplitude booms for four classes of aircraft size from subscale demonstrator to full-sized airliner. For a given outdoor PL, the annoyance to subscale aircraft booms was not significantly different from that for full-scale aircraft booms. This confirmed that outdoor PL can be used to evaluate supersonic aircraft designs regardless of size. These results show evidence that human response to booms from a subscale demonstrator are relevant to a full-size aircraft and help justify plans for use of a subscale demonstrator for community studies. However, the results were limited to isolated booms with no rattle.

A series of tests was conducted to investigate the human response to rattle and to combined boom and rattle (Loubeau et al., 2013c). Using binaural recordings of rattle played back over headphones, the study found differences in annoyance between rattle sounds for the same PL. Rattle sounds from structural elements such as windows, walls, and doors were judged more annoying than rattle from smaller objects, and the study confirmed the presence of elevated annoyance indoors when rattle is present.

Rattle studies conducted in NASA's IER facility using a more realistic sonic boom playback and indoor environment (Rathsam et al., 2015; Loubeau, 2018) found that rattle increased indoor annoyance. Window rattle sounds reproduced for a variety of window types demonstrated that the average increase in annoyance due to rattle was equivalent to an increase in exterior boom PL of 4 dB, confirming the headphone test rattle penalty of 3-9 dB.

Vibration studies were also conducted in the IER (Carr and Davies, 2015; Rathsam and Klos, 2016; Rathsam et al., 2018) using vibration isolators on the test chair legs and shakers attached to the seat bottom. For vibration levels near the high end of what is predicted to occur in buildings (Klos, 2016), vibration penalties up to 10 dB were observed, indicating that vibration also plays a role in the indoor perception of sonic booms.

Startle is another possible factor in the human response to sonic booms. Earphone studies examined startle in conjunction with annoyance and loudness for impulsive sounds (Marshall and Davies, 2011, 2012) and found that startle ratings were strongly correlated with annoyance due to the abruptness of the initial shock and resulting high-frequency energy. Subjective judgments of startle were compared to physiological responses using measured skin conductance, heart rate, and electrical activity of three neck muscles. Although subject-to-subject and day-to-day variability in the physiological responses were observed, their association with startle was rare, and it was concluded that low booms are below the threshold of consistent startle responses.

Community Studies

Data relating the response of communities to low-amplitude sonic booms are needed by the international regulatory agencies so they can decide if supersonic overland flight will be permitted. If so, the regulators will need to establish low-boom criteria for certification of supersonic overland aircraft. Their decisions will need to be based on both single-event and cumulative impacts. Community testing protocols are under development to gather these response data. Historically, noise dose-response testing for transportation sources and for military installations with impulsive noises such as booms, artillery, and blast noise has related the percentage of community members highly annoyed by the noise to cumulative metrics such as day-night level (DNL).

In 2011, a NASA community study was conducted of the response of 100 Edwards Air Force Base (EAFB) California residents to sonic booms. The waveforms and sonic boom perception and response (WSPR) program was designed to test and demonstrate the applicability and effectiveness of techniques to gather data relating the human subjective response to multiple low-amplitude sonic booms, in essence a dose-response test. It included a range of sonic booms from low amplitude (generated using the low-boom dive maneuver) to higher amplitude from conventional overflight and military operations in the area (Fidell et al., 2012; Page et al., 2014).

The WSPR program addressed the following: (1) design and development of an experimental design to expose people to low-amplitude sonic booms; (2) development and implementation of methods for collecting acoustical measures of the sonic booms in the neighborhoods where people live; (3) design and administration of social surveys to measure people's reactions to sonic booms; and (4) assessment of the effectiveness of various elements of the experimental design and execution to inform future, wider scale testing. Sonic boom measurements were gathered in the residential community and statistical methods were developed for assessing the subjective response to low booms.

The subjective response data-analysis methods allow the identification of dose-response curves relating annoyance to the noise exposure, although this particular dataset reflects responses from an acclimated community and might not be reflective of people living in areas not routinely exposed to sonic booms. Single-event dose-response curves were obtained for a variety of noise metrics using measured noise levels from a distributed set of noise monitors. Another important element of the WSPR test was the consideration of not only a single-event response but also a daily cumulative response and hence was designed to take into account the number of daily potential future supersonic operations. Past studies (Salamone, 2009; Rachami and Page, 2010) suggested that a variety in the number of exposures would be expected across the United States from future operations, with a maximum of up to 12 sonic booms daily.

To understand the cumulative impacts, cumulative daily exposures were computed (C-weighted DNL, CDNL) for the WSPR participants and compared with prior sonic boom studies in the 1960s and 1970s. An example comparison of these data (Loubeau, 2013) to historical data (Borsky, 1965) is shown in **Figure 3**, which presents the percentage of test subjects who were highly annoyed by the day's boom events as a function of CDNL for each day. Although the WSPR study was primarily a methodological test in preparation for future studies with a low-boom demonstrator aircraft, the daily annoyance results are remarkably similar to those from the 1965 Borsky report.

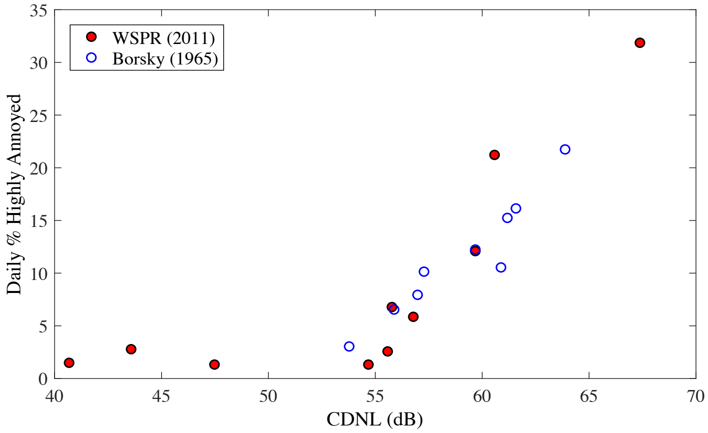

Figure 3. *Dose-response data from the waveforms and sonic boom perception and response program (WSPR) 2011 study (Loubeau, 2013) compared with data from a 1960s sonic boom field study (Borsky, 1965). CDNL, C-weighted day-night level.*

Mach Cutoff

It is possible to fly supersonically without creating an audible sonic boom on the ground by taking advantage of atmospheric refraction where the sonic boom pressure waves are turned upward before reaching the ground. The speed at which this occurs is referred to as the Mach cutoff and is a function of the atmospheric conditions and flight altitude. Mach cutoff relies on the fact that the speed of sound at flight altitude is lower than that on the ground due to the colder upper air temperatures. The possibility is being explored of mixed Mach number conventional N-wave design aircraft that will fly just below Mach cutoff over land (nominally between Mach 1.0 and 1.15) and at higher supersonic speeds over water where supersonic flight is not currently prohibited (Matisheck, 2017). Even though the sonic boom itself does not reach the ground when flying below the Mach cutoff, some of the energy from the sonic boom pressure disturbance transitions into an evanescent wave, passes into the shadow side, and can reach the ground as an acoustic signal where it often sounds like rumbling or distant thunder. The NASA far-field investigation of no-boom thresholds (FaINT) test captured an empirical dataset of these evanescent waves (Cliatt et al., 2016).

Analysis of the Mach cutoff (Plotkin et al., 2008) has examined the viability of Mach cutoff flights across the United States, while recent research funded by the Federal Aviation Administration (FAA) has explored the sensitivity of different atmospheres on overpressure and loudness levels (Busch et al., 2017). As a consequence, efforts are underway to investigate human perception of these Mach cutoff sounds (Ortega et al., 2018) using the FaINT dataset.

Sonic Boom Metrics

There is a need to identify noise metrics to quantify the noise exposure in dose-response curves of community test data. These metrics, which can leverage existing metrics for commercial, military, and impulsive noise sources, must be computed using outdoor signals (even if the majority of people spend most of their time indoors), analogous to the process for subsonic aircraft noise certification and environmental assessments.

A meta-analysis study was conducted to combine results from several years of laboratory testing into a meta-analysis to evaluate candidate noise metrics calculated on outdoor signals, with the objective of identifying the best subset of metrics (Loubeau et al., 2015). An exhaustive list of approximately 70 metrics was compiled from standards and literature; expert judgment, including consideration of nonacoustic factors, resulted in 25 metrics being chosen for quantitative analysis. Three categories of metrics were defined: (1) engineering metrics to describe aspects of the sound, (2) loudness metrics to account for human perception of sound, and (3) "hybrid" metrics that combine several metrics into one model. Based on laboratory studies of isolated outdoor and indoor booms (Loubeau et al., 2015) and incorporation of rattle and vibration effects (DeGolia and Loubeau, 2017), analyses resulted in six single-event metrics: PL, ASEL, BSEL, DSEL, ESEL, and ISBAP (terms defined in *Single-Event Metrics*). This set of metrics will be used in the development of single-event and cumulative dose-response curves from future studies of community response to sonic booms.

Single-Event Metrics

- A-, B-, C-, D-, and E-weighted sound exposure levels (ASEL, BSEL, CSEL, DSEL, and ESEL, respectively) combine both the intensity of the sound and its duration and represent the total sound energy in an event accounting for the spectral weighting factors that amplify the higher frequency content and deemphasize the lower frequency content to various degrees.
- PL is the perceived level in decibels based on Stevens Mark VII equal loudness (Stevens, 1972). It includes very low frequency (1-Hz) energy and accounts for shock rise times and overpressure for N-waves and shaped sonic booms (Shepherd and Sullivan, 1991).
- Indoor sonic boom annoyance predictor (ISBAP) is a hybrid metric that applies a low-frequency correction factor to PL and is defined as ISBAP = PL + 0.4201*(CSEL − ASEL) (Loubeau, 2014).

Cumulative Metrics

- DNL is the day-night average sound level that accounts for all noise events in a 24-hour period with a 10 dB nighttime noise penalty for events occurring between 10 p.m. and 7 a.m. local time.
- CDNL is the DNL calculated with C-weighted sound levels.
- PLDN is the day-night average PL that accounts for all noise events in a 24-hour period and is based on PL (McCurdy et al., 2004).

Future Outlook

On April 3, 2018, NASA announced a new project with Lockheed Martin to build a low-boom flight demonstrator experimental plane. Now known as the X-59 Quiet SuperSonic Technology (QueSST) aircraft, this vehicle will be a purpose-built low-boom aircraft capable of creating shaped sonic booms and is intended to provide crucial data that can potentially enable commercial supersonic passenger air travel over land. NASA intends to gather community response data for delivery to the FAA and ICAO from which new rules for supersonic commercial overland flight may be developed and adopted. Researchers have been actively developing the subjective dose-response procedures and protocols for this testing.

Although tremendous progress has been made, two of the areas that have not received significant research attention are the potential for sleep disturbance from low booms and techniques to model and mitigate the effect of focused booms. As illustrated in **Figure 2**, a crescent of higher amplitude "focused" sonic boom occurs during transition from subsonic to supersonic flight. Preliminary focused boom modeling and analysis methods developed as part of NASA's Superboom Caustic Analysis and Measurement Program (SCAMP; Page et al., 2015) suggested that shaped booms do remain shaped and retain their loudness reduction benefits even in focal zones. The SCAMP also identified the trend that higher altitude and lower acceleration through transition will help minimize the focus boom loudness from low-boom aircraft. It is anticipated that data can be gathered from the flight testing to further investigate sonic boom focal zones.

Other factors not considered in the subjective studies to date include booms from other parts of the trajectory outside the cruise design point, secondary booms, noise in the shadow zone beyond lateral cutoff, and sleep disturbance relating to any of these conditions.

Summary

Sonic boom simulators and special aircraft maneuvers have been used to investigate human annoyance to sonic booms in outdoor and indoor environments. The most important factors have been studied separately to shed light on the role they each play in human perception. Studies have confirmed the viability of using an outdoor metric to predict human response indoors despite differences in noise dose indoors. Results indicate that low sonic booms, or sonic thumps, are much less annoying than conventional sonic booms, although annoyance levels need to be confirmed with community testing.

Laboratory test results have been used in meta-analyses to evaluate candidate noise metrics, and six metrics are recommended for further consideration in development of a new sonic boom noise certification standard. This subset of metrics will be used in future analyses of community field data using a purpose-built low-boom flight demonstrator. Present efforts at NASA are geared toward preparations for testing and further development of test methods for gathering both the estimated noise exposure and the human annoyance data.

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BioSketches

Alexandra Loubeau is a research aerospace engineer at the NASA Langley Research Center, Hampton, VA. She received her MS and PhD in acoustics from The Pennsylvania State University, State College, and has been researching sonic boom acoustics since then. As the team lead for sonic boom community-response research at NASA, she is involved in the planning, execution, and analysis of experimental, modeling, and psychoacoustics research. Alexandra enjoys playing the violin in a local orchestra, swimming, and learning languages.

Juliet Page, a physical scientist with the US Department of Transportation Volpe Center, Cambridge, MA, has spent the last 32 years conducting and directing theoretical and experimental research programs in acoustics for the aviation and transportation sector. As a leading expert in the field of sonic boom, she has directed numerous NASA, Federal Aviation Administration (FAA), Airport Cooperative Research Program (ACRP), and Department of Defense environmental analysis, measurement, research, and NextGen programs and has been instrumental in the development of acoustic measurement protocols. She is a member of several US and international standards and technical committees. In her spare time, Juliet enjoys boating on Chesapeake Bay and making glass beads.